THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Importance of the demand-supply balance in district heating systems

DMYTRO ROMANCHENKO

Department of Space, Earth and Environment

CHALMERS UNIVERSITY OF TECHNOLOGY

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Division of Energy Technology
Department of Space, Earth and Environment
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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Chalmers University of Technology

Abstract

In line with global efforts directed against climate change, the building sector will have to undergo significant changes in terms of its energy use, along with the transformation of the energy system. The scope of this thesis is limited to the energy supply and demand within district heating (DH) systems, with the emphasis on the space heating demand in buildings. The overall aim is to improve our understanding of how the demand-supply balance can be maintained in the future.

This work applies a techno-economic optimization model that was developed to study optimal dispatch and utilization strategies for DH systems, including endogenous calculation of the space heating demand in buildings, thereby enabling a feedback mechanism between demand and supply. The present work uses the building stock and DH system of Gothenburg, Sweden as a case study, although generalizable insights are derived.

The results suggest that the lowest system cost for transforming urban heating systems is obtained through a combination of investments in energy conservation measures (ECMs) in buildings and in heat generation/storage technologies in DH systems. As expected, the application of energy demand reduction targets results in greater investments in ECMs than would result from considering only developments due to fuel and electricity price increases (without targets) and, thus, the consequences of lower investments in heat generation capacities in DH systems. We also show that the realized demand response (DR) in buildings significantly influences the total system heating load of a DH system through smoothening load fluctuations. DR implemented via indoor temperature deviations of as little as +1°C can effectively smoothen short-term (daily) system load fluctuations by up to 18% and can reduce the total system running cost by up to 4% over a period of 1 year. The cost reduction stems from increased output from base-load generation units and significantly less-frequent use of peaking units. However, for load variation management on longer time scales, the application of centralized thermal energy storage systems is more beneficial than the DR from buildings. Finally, the results reveal the synergy between DH systems and the power sector, in that flexible utilization of combined heat and power plants and heat pumps supplemented with the energy storage potential of DH systems delivers additional economic benefits to DH systems owners and is a reliable service provider to the electric power system.

Keywords: Space heating, demand response, flexibility, district heating, buildings, thermal energy storage, optimization

List of publications

This thesis is based on the following appended papers, which are referred to in the text by their assigned Roman numerals:

I. Romanchenko, D., Odenberger, M., Göransson, L., Johnsson, F. Impact of electricity price fluctuations on the operation of district heating systems: A case study of district heating in Göteborg, Sweden (2017) *Applied Energy*, 204, pp. 16-30.

II. Romanchenko, D., Kensby, J., Odenberger, M., Johnsson, F. Thermal energy storage in district heating: Centralised storage vs. storage in thermal inertia of buildings (2018) *Energy Conversion and Management*, 162, pp. 26-38.

III. Romanchenko, D., Nyholm, E., Odenberger, M., Johnsson, F., Flexibility Potential of Space Heating Demand Response in Buildings for District Heating Systems (2019) *Energies*, 12 (15), 2874.

IV. Romanchenko, D., Nyholm, E., Odenberger, M., Johnsson, F., Impacts of demand response from buildings and centralized thermal energy storage on district heating systems. Submitted for publication in *Applied Energy.*

V. Romanchenko, D., Nyholm, E., Odenberger, M., Johnsson, F., Balancing investments in building energy conservation measures with investments in district heating – A Swedish case study. Submitted for publication in *Energy and Buildings.*

Dmytro Romanchenko is the principal author of **Papers I–V**. Professor Filip Johnsson, who is the main academic supervisor and examiner, contributed with discussions and editing to all five papers. Mikael Odenberger, who is the co-supervisor, contributed with in-depth discussions and editing to all five papers. Lisa Johansson contributed with discussions and editing to **Paper I**. Johan Kensby contributed with method development, discussions and editing to **Paper II**. Emil Nyholm contributed with method development, data processing, discussions and editing to **Papers III–V**.

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Abbreviations and nomenclature

Abbreviations

BITES	Energy storage *via* Building Inertia Thermal Energy Storage
BS	Building Stock
CHP	Combined Heat and Power
DH	District Heating
DR	Demand Response
EBUC	Energy Balance Unit Commitment
HOB	Heat-only Boiler
HP	Heat Pump
HWT	Energy Storage *via* Hot Water Tank
MFD	Multi-Family Dwelling
NRB	Non-Residential Building
RDLV	Relative Daily Load Variations
RWLV	Relative Weekly Load Variations
SFD	Single-Family Dwelling
TES	Thermal Energy Storage
UC	Unit Commitment
UCS	Unit Commitment with Storage

Nomenclature

Demand	The amount of energy required ("wanted") by a consumer in order to fulfil some need(s)
Demand response	Changes in the end-use patterns (e.g., energy use) of consumers from their normal consumption patterns in response to changes in some kind of incentive, e.g., a time-dependent price signal
Load	The amount of energy delivered to a consumer
Optimal dispatch	The short-term determination of the optimal operation of a number of generation units meeting the specified objective, e.g., fulfilling the system load at the lowest cost, subject to a number of constraints
Peak shaving	Demand response strategy, which implies a reduction in energy consumption during the peak-load hours
Thermal inertia	Resistance to a change in temperature
Valley filling	Demand response strategy, which implies an increase in energy consumption during the low-load hours

1. Introduction

According to the International Energy Agency (IEA), approximately one-third of final energy consumption globally is linked to the building sector, making it responsible for about one-third of total, global, energy-related carbon dioxide (CO_2) emissions [1]. Thus, the building sector is considered crucial for the changes that need to occur towards meeting the global emission reduction targets. Considering that buildings are long-term assets, and that around 75%–90% of the buildings standing in the EU today are expected to still be in use in Year 2050 [2], the energy performance of existing buildings must be improved. Nevertheless, the transformation of the building sector should not be treated as a separate demand side-focused phenomenon. The Energy Performance of Buildings Directive (EPBD) established by the European Commission requires that *"Member States should seek a cost-efficient equilibrium between decarbonizing energy supplies and reducing final energy consumption"* [3]. Thus, the success of urban energy systems is to a large extent expected to rely on identifying and exploiting synergies between energy demand and supply.

Space heating and hot-water use account for 79% of the total final energy use in EU households and are mainly reliant on fossil fuels [4]. Essentially, there are two conceptually different ways to decarbonize the supply-demand chain of the heat usage in buildings [5]. The first option is deep energy renovations to buildings, leading to low-energy building stocks with very low demand or even without any need for heating. The second option is to transform the supply side, for example, by making use of excess heat from industries and waste incineration, as well as the utilization of geothermal and large-scale solar thermal energy together with large-scale heat pumps and Thermal Energy Storage (TES). The overall goal would be to accommodate larger shares of renewable energy resources within the energy system, which would promote decarbonization. In this context, coordination and a systems perspective are important. For instance, the Heat Roadmap Europe study [6] has shown that 50% integration of District Heating (DH) across the whole EU and sector integration could be more efficient than a decentralized (primarily based on individual heating) system and, at the same time, would allow for larger shares of renewable energy in the energy system at a lower cost (similar conclusions are drawn in other studies [7, 8]). In Sweden, DH systems are well-established and presently account for around 55% of the total Swedish space heating and hot-water demand [9]. In Multi-Family Dwellings (MFDs), this proportion reaches 92%, which motivates the research presented in this thesis.

One of the main challenges associated with the operation of DH systems is the significant variations in heat demand (including long-term seasonal and short-term daily variations) that occur and result in part-load operation and frequent start-ups and shut-downs for the heat generation units. Moreover, even though approximately 90% of the total heat generated in Swedish DH systems is derived from the burning of biofuels and waste incineration, fossil fuel-fired peaking Heat-Only Boilers (HOBs) are still commonly used for load following and result in annual emissions of 2.75 $MtCO_2$, corresponding to 5% of annual Swedish CO_2 emissions [10]. Thus, adding flexibility to DH systems might reduce the levels of utilization of peaking units and facilitate decarbonization of the heat supply (*cf.* examples of flexibility options in DH systems in Figure 1). Swedish DH systems are also of special interest because they have a high penetration rate of Combined Heat and Power (CHP) plants and Heat Pumps (HPs), which in 2013 accounted for 40% and 8%, respectively, of the total annual heat generated by DH systems [11]. Smart operation of CHP plants and HPs provides considerable potential for flexibility services that DH systems can provide to the electric power sector and, therefore, facilitate the integration of variable renewable energy resources into the energy system.

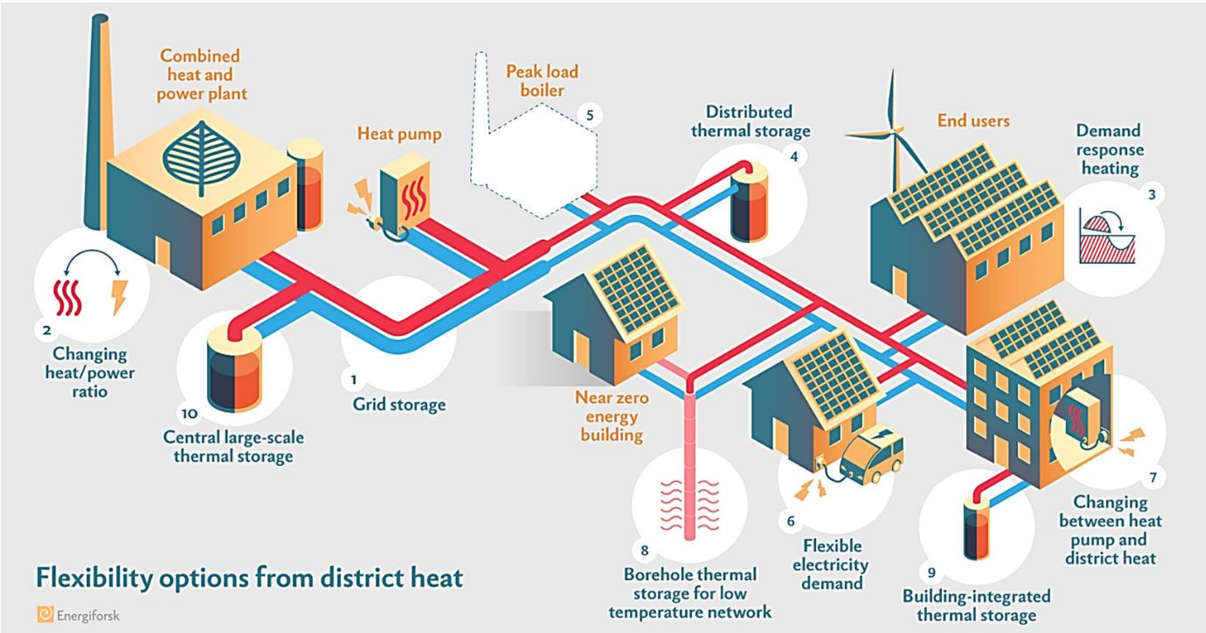

Fig. 1. Schematic of flexibility options in district heating systems [12].

Overall, one of the major components of the Swedish energy system is DH systems, which is also true for many other countries. Understanding the future heating demand from the building sector, as well as the linkages between the electric power sector and DH systems is of importance when exploring the development of the energy system in a sustainable way. This is investigated in the present work.

1.1 Aim and scope of the thesis

Strengthening the interplay between the components of the energy system is necessary for a successful transition to a sustainable future. The overall aim of this work is to increase our understanding of how the future energy demand in buildings will look and how it can interact with (influence and be influenced by) the energy supply side. This thesis focuses on the heating part of the energy supply, more specifically on DH, and the space heating demand from buildings. The overarching hypothesis is that flexible heating demand from buildings, when controlled together with the heat generation in DH systems, i.e., considering both the demand and supply sides at the same time, can improve the efficiency and reduce the cost of heating in urban heating systems. Developing and refining a modeling methodology that supports this hypothesis are the objectives of this work. In addition, the benefits of the interactions between DH systems and the power sector are investigated. More detailed research questions of this work are as follows:

- How to balance future investments in Energy Conservation Measures (ECMs) in buildings and in heat generation and storage technologies in DH systems in a cost-optimal way?
- What type of DR behavior, achieved by allowing for indoor temperature variations, is expected from buildings if a least-cost urban heating system development is considered?
    - Will the physical properties of the buildings influence the potential DR role?
- If DR in buildings is widely applied and acts as to minimize the system cost, what are the consequences of such behavior for the future demands from specific buildings, as well as for the total heating load of DH systems?
- In what way does the impact from DR in buildings differ from that of a centralized energy storage, e.g., a hot-water tank or a seasonal pit TES? Are DR and TES competing or complementary options?
- What are the implications of a future with highly volatile electricity prices for the interplay between DH systems and the power sector?

These research questions are addressed by modeling relevant parts of the energy system. The modeling utilizes a techno-economic optimization model, which was developed and adjusted to tackle the research questions. In **Papers I** and **II**, the system boundary is drawn around the heat supply side - a DH system, which means that parameters such as electricity prices and the total system heating load are given as inputs to the model. In **Papers III–V**, the studied/modeled systems include a city-level DH system, as well as the Building Stock (BS) of the city. In this model setup, the space heating demand from the buildings is endogenously calculated at the same time as the heat supply. The geographic scope with regards to the description of the BS and the DH is limited to the city of Gothenburg, Sweden in all the appended papers. Nonetheless, many of the conclusions are generalizable to other systems. While the results of the modeling represent neither a prediction nor a prescription of the near-term to long-term future, they provide insights into the dynamics and outcomes of the potential interactions between flexible energy demand in buildings and heat generation in DH systems.

1.2 Contributions of the thesis

The objectives listed in Section 1.1 are addressed in the five appended papers, which are summarized below.

Paper I investigates the impacts of short-term (hourly) and long-term (seasonal) variations in electricity prices and heating loads on the operation of DH systems. The paper provides insights into the levels of flexibility of heat generation units, which are important to understand before studying the potential of DR from buildings and TES in DH systems. Furthermore, it improves our understanding of the interactions between DH systems and the power sector. In **Paper I**, a Unit Commitment (UC) optimization model of a DH system is developed, which is also used as the basis for the further model developments in **Papers II–V**.

Paper II investigates the benefits of applying TES in a DH system. Two types of TES are investigated: centralized Hot-Water Tank (HWT); and decentralized storage via the thermal inertia of buildings. The representation of the latter is based on an empirical test, which was conducted (by others) on MFDs and exploits the principle of temporal over-heating and under-heating of buildings. The work is based on the UC optimization model, which is further developed to include the two TES types and, therefore, is referred to as the UC with Storage (UCS) model. The comparison of the two TES types, which are fundamentally different in nature (supply vs. demand side impacts), when studied using the same modeling approach and applied to the same DH system (one at a time), is considered novel.

Papers III and **IV** investigate the potential for flexible space heating demand, i.e., DR, in buildings, as well as its effects on the system (city's) heating load and the operation of DH systems. The DR from the space heating in buildings is enabled by allowing for deviations in the indoor temperature of the buildings, i.e., temperature variations are allowed within a predefined temperature range. In **Paper IV**, a centralized TES is also included in the modeling, which allows for the identification of reciprocal effects of decentralized and centralized flexibility measures in DH systems. **Paper III** studies the BS and DH system of Gothenburg as of Year 2012, while **Paper IV** projects the system into Year 2050. The work is based on a demand-supply integrated model, which is developed by integrating the UC model of a DH system (developed in **Paper I**) with a physical energy balance model of a BS (developed elsewhere).

Paper V examines the cost-optimal balance between the reduction in space heating demand in buildings, achieved through investments in ECMs, and the development of DH systems. The investigated ECMs include the insulation of walls and roofs, replacement of windows, and installation of ventilation heat recovery systems. This paper includes three modeled scenarios, which differ with respect to the space heating demand reduction targets for buildings (European and Swedish energy demand reduction targets for buildings are taken as a basis for two of the scenarios). Special emphasis is placed on the choice of ECMs and types of buildings chosen for the energy refurbishments. The work relies on an investment model, which is a modification of the demand-supply integrated model (developed in **Paper III**) and spans the period of 2020–2050.

The model applied in **Papers III–V** allows for concurrent optimization of the space heating demand in buildings and the heat generation in a DH system, i.e., explicitly accounts for the feedback mechanism between demand and supply (further explained in Chapter 3). The inclusion of the feedback dynamics is considered to be the main modeling contribution of this work, in that it fills a knowledge gap in the literature. These papers also contribute to the research field by investigating the flexibility potential of a BS on a system (city) level, in contrast to the single-building analyses applied in the majority of related studies.

1.3 Outline of the thesis

This thesis is based on the five appended papers and this extended summary. The extended summary consists of six chapters, with this *Introduction* being the first. Chapter 2 introduces some basic information and concepts that are relevant to this thesis and that may be useful for readers who are not acquainted with the field. A brief literature review is also provided in Chapter 2. Chapter 3 describes and motivates the modeling approaches and the assumptions that are applied in the appended papers. Chapter 4 presents and explains the input data used in the modeling. The main findings from the presented work and discussions thereof are included in Chapter 5. Finally, Chapter 6 summarizes the most important conclusions from the work, while Chapter 7 suggests some avenues for future research.

2. Background

This chapter gives a short introduction to the main concepts in focus in this thesis.

Basics of district heating systems

A DH system comprises a network of pipes that connect heat consumers, mainly residential and commercial buildings, with a number of centralized heat generation units. DH is designed to satisfy consumers' space heating and hot-water demands. After heat is generated, it is distributed to the consumers in the form of steam (older systems), pressurized hot water, or atmospheric-pressure hot water in a network of insulated pipes, usually buried underground. The temperature of the water in the supply networks of contemporary DH systems is often <100°C, whereas "4th generation DH systems" can use water-supply temperatures of around 50°C [13, 14]. The generation mix in DH systems usually consists of HOBs, HPs, and electric boilers, which generate heat exclusively, as well as CHP plants, which are able to generate both heat and electricity. Some DH systems also accommodate units that make use of geothermal or solar energy for heat generation. In addition, Swedish DH systems, especially those in the large cities, make use of waste heat, which would otherwise be released to the surroundings and be lost, e.g., industrially generated excess heat. In Year 2015, the share of waste heat from total heat deliveries by DH systems in Sweden was 32% [15].

DH systems generally have a number of advantages over individual heating systems. Centrally generated heat normally provides higher fuel efficiencies and, thereby, lower fuel consumption levels, as compared to decentralized heat generation. Furthermore, as mentioned earlier, the use of CHP plants and HPs in DH systems can establish an important interlinkage with the electric power system, in that DH systems can exploit low-cost electricity from wind and solar energy during periods of high output and can also act an important suppliers of electricity when there is lower levels of variable renewable power generation [16]. However, these advantages come at a cost, in that the investments required for DH infrastructures are large and entail a long-term financial commitment, as compared to investments in decentralized heating solutions. Furthermore, due to the losses incurred in the piping network, DH systems are less competitive in regions with low population (consumer) densities. Further insights into the technical, economic, environmental, market, and institutional contexts of DH both globally and, with a deeper analysis, in Europe can be found in the review of Werner [17].

Heating-load variations

A characteristic shared by energy (electric power and heating) systems is a demand-driven load that is not constant over time. The heating load in heating systems varies both seasonally and daily. Seasonal heating load variations arise from the requirement to maintain a constant indoor temperature in the connected buildings even though the outdoor temperature changes significantly across seasons. In addition, social factors contribute to the seasonal variations in heat load, in that inhabitants usually stay indoors longer during the colder parts of the year and tend to increase their hot-water use, as compared to the warmer months. Daily heating load variations are driven to a greater extent by social factors than by climatic factors, even though they are also influenced by, for example, day-night temperature differences. In residential buildings, the level of hot-water use during night-time is much lower than during day-time, since the inhabitants are usually asleep at night. In addition, some people prefer to lower the indoor air temperature by a few degrees at night-time. As most commercial buildings are not in use during night-time, the ventilation rates and building temperatures can be set lower than during the day. This behavior significantly influences the levels of heat supplied to the customers over the course of a day, i.e., causes daily heating load variations.

Another feature of most of the present energy systems is that there are a few integrated storage options. Therefore, it is necessary to satisfy the system load on a just-in-time basis, i.e., there is a significant requirement for maintaining a balance between supply and demand. Nevertheless, for DH systems, this requirement is not as crucial as it is for the power system, owing to the small buffer in terms of thermal inertia created by the piping network itself. However, if the level of heat generation in the system is lower than the total system heating load the heat-consumers will be affected differently. Peripheral customers (the ones located farthest from the heat generation units) will experience an under-supply of heat, while customers closer to the heat generators may not be affected at all. This is due to the pressure drop along the DH piping network that connects the customers. Therefore, variations in the heating load must be dealt with meticulously by the generation capacities, in order to provide the same quality of heat supply to all the customers.

Variation management

The varying heating load in heating systems can be met through two main strategies: (i) a supply side-oriented strategy that makes the heat supply more flexible; or (ii) a demand side-oriented strategy, whereby the heating demand becomes flexible. Historically, the most commonly adopted solution to the problem of varying load has been to make the supply side flexible by installing so-called "load following" or "peaking" heat generation units (in addition to base-load and intermediate-load units, which cover most of the load). Peaking units are able to change their outputs in a flexible manner within a short time period, e.g., within minutes, usually at the expense of high running costs, as compared to the running costs of base-load units. Thus, the more variations that a DH system experiences, the more peaking capacity is needed, if following the first strategy and, consequently, the total cost of the heat deliveries increases. At present, peaking units are often fossil fuel-fired, so load variations can lead to high CO_2 emissions associated with the heat generation.

Another option to make heat supply more flexible is to add TES to the supply side. TES systems can be divided into three types: 1) sensible heat storage, in which thermal energy is stored by heating or cooling a liquid or solid storage medium; 2) latent heat storage using phase-change materials; and 3) thermochemical storage using chemical reactions to store and release thermal energy. The types of storage most commonly applied in DH systems are water-based sensible TES systems, owing to their low costs compared to latent or thermochemical TES systems. TES systems can also be classified as either centralized (e.g., a single standing borehole TES) or decentralized (e.g., HWTs in households). The implementation of TES in energy systems (at either the supply side or demand side) results in the TES acting as a buffer for the energy balance, thereby shifting the energy generation/demand from one period in time to another, e.g., supplying peak demand with the heat generated earlier during a period of low demand, which is referred to as *peak shaving* and *valley filling* (Figure 2). Peak shaving and valley filling result in a smoother overall load, thereby enhancing the possibility to use base-load generation units with low running costs and decrease generation from costly peaking units.

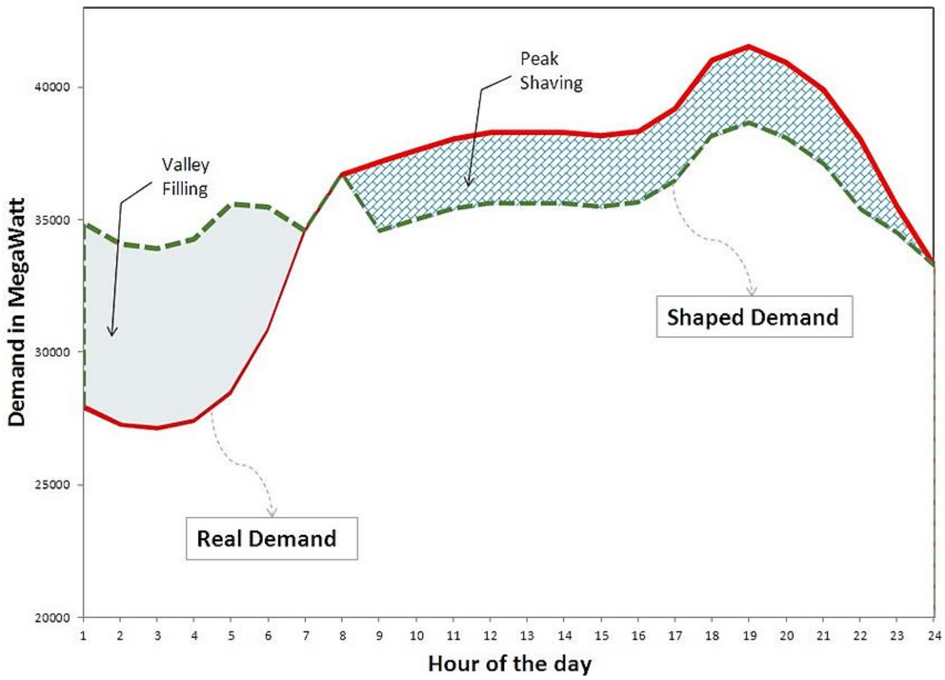

Fig. 2. Schematic showing peak shaving and valley filling in energy systems [18].

With respect to heating systems, flexible demand can be achieved by time-shifting the space heating demand or the hot-water use of buildings. Since hot-water use is driven by many factors (mainly occupant-related [19]), for which change is assumed to be difficult, the greatest potential for ensuring demand flexibility in buildings lies in the space heating demand. Flexible space heating demand from buildings is achieved by activating DR, which is realized by initially increasing the amount of heat delivered to buildings (again, valley filling), followed by a decrease in the amount of heat delivered to buildings (peak shaving), assuming that small deviations of the indoor temperature are acceptable to the inhabitants. This concept can also be described in terms of using the thermal inertia of buildings as TES. As compared to centralized TES, the usage of buildings for load variation management confers some advantages and disadvantages. The potential benefits from a centralized TES can be limited by bottlenecks in the DH piping networks, while the buildings used for storing heat are dispersed and readily available in all of the city to provide DR services. However, activation of DR in buildings may entail organizational challenges. While centralized TES systems, e.g., a HWT, are assumed to be 100% owned and operated by the DH system operator, utilization of buildings as TES relies on the establishment of a business model that involves both the DH operator and homeowners, as well as the installation of adequate control systems. Furthermore, it also requires that indoor thermal comfort can be maintained at a level that is acceptable to the inhabitants/homeowners.

2.1 Related research

The scope of this work covers the topics of heat generation in DH systems, energy demand for space heating in buildings along with the buildings' potential for DR, and the benefits of considering both the demand and supply sides when investigating (through modeling) the future of the energy system. Here follows a brief review of the relevant research, as well as the motivation for the model development of this work.

Energy systems modeling

One of the goals for global sustainable development is to *"ensure access to affordable, reliable, sustainable and modern energy for all"* [20]. Achieving such a goal is obviously challenging considering uncertainties regarding future resource availability and pricing, technologic innovations, demand growth (or decrease), and energy and environmental policies. Energy system models are valuable tools that provide comprehensive and robust information on the transformation of the energy system under a variety of different assumptions [21, 22, 23]. The outcomes from such models are often cited by governmental institutions, politicians, NGOs, and the scientific community. However, it should be borne in mind that the outputs of the energy system models are mainly insights that challenge our working assumptions and mental models, rather than quantitative predictions [24, 25].

Within the field of energy systems modeling, bottom-up techno-economic energy system optimization models are commonly used to explore future developments of the energy system, providing a relatively high degree of technological detail. Bottom-up models usually assume perfect foresight and optimize the development of the energy system from a social-planning perspective, thus producing normative results that can be considered as policy-related insights for, as examples, optimal installation rates and utilization strategies of energy technologies. Examples of widely used energy systems optimization models applied to explore possible developments of the energy system (including DH systems) at the regional, national and worldwide scales are MARKAL [26], TIMES [27], and MESSAGE [28], and open source models such as OSeMOSYS [29]. Given their high level of technological detail, these models require simplifications, e.g., spatially aggregated regions or technology-type aggregates, in order to remain traceable and solvable. Another simplification made in large, bottom-up energy optimization models is temporal aggregation, i.e., the representation of a year using a number of time slices. This simplification can be assumed to be acceptable for modeling energy systems that are based predominantly on dispatchable energy generation units. However, larger shares of variable renewable energy resources require higher spatial and temporal resolutions to answer definitively questions about the development of the energy system [30]. A possible solution is to supplement the outputs from the larger energy systems models with the results from comparatively smaller models developed for specific purposes, e.g., models with high technology-type and temporal resolutions, when studying the benefits of the interplays between the electric power system and DH systems with available CHP plants and HPs (as in **Paper I**).

Modeling the operation of DH systems

As indicated above, heating load variations directly affect the operation of DH systems and, therefore, have caught the attention of other researchers in the past. Gadd and Werner [31, 32] have developed and applied a generic assessment method to describe load variations in 20 Swedish DH systems. They conclude that there is no standard heating load pattern in DH substations (i.e., buildings connected to DH substations have very different heat consumption profiles), which implies that the scheduling of heat generation units in DH systems is a continuous and challenging process. Computer-based, techno-economic UC optimization models are widely used to study the operation of DH systems. UC models provide the possibility to identify the optimal commitment and dispatch of energy generation units that fulfil a required energy demand at each time-step over the modeled period. A comprehensive review of the different optimization techniques, as well as the optimization tools applied to DH systems has been provided by Sameti and Haghighat [33]. For example, Wang et al. [34] and Carpaneto et al. [35] have developed UC models to determine the optimal configurations and operating strategies of CHP-based DH systems in Finland and Italy, respectively. Chen et al. [36], Yang et al. [37], and Fang et al. [38] have applied UC models with the focus on maximizing the wind power penetration rate in the energy system using the flexibility provided by CHP plants that are available within DH systems. While the UC models [34-38] have been developed as single-objective models, e.g., minimization of the costs, some studies have focused on multi-objective optimization, i.e., simultaneous optimization of costs and CO_2 emissions [39, 40, 41].

Several UC models have also been developed and applied to study the utilization strategies and benefits of having TES in DH systems. The majority of these studies have focused on water-based centralized TES systems. For example, Bachmaier et al. [42] and Oluleye et al. [43] have used techno-economic optimization models to design and optimize DH systems that contain TES units designed to improve the flexibility of CHP plants. Ameri et al. [44] and Buoro et al. [45] have used optimization models to study the effects of integrating solar thermal plants together with TES into heat and electricity generation in local energy systems.

Most of the UC models developed in the abovementioned works use a linear programming approach, which limits their potential to represent some important characteristics of DH systems, e.g., limitations linked to the minimum output level and the start-up and shut-down characteristics of the heat generation units. Furthermore, the majority of these works either have hourly resolution and cover a short time-span (from 1 day to 1 month) or they adopt the strategy of discretization of an entire year into specific time-bands. This limits their potential to investigate the impacts of both the short-term and long-term variations in the electricity prices, induced by wind power, and the long-term heat saving potentials of TES systems on the operation of DH systems. These limitations related to the previous research studies formed in part the motivation for the development of the techno-economic, mixed-integer UC model of a DH system applied in this work (further explained in Sections 3.2-3.3).

Modeling space heating DR from buildings

The potential of space heating DR in buildings, i.e., the utilization of the building thermal inertia as TES, has been studied by a number of researchers (reviewed in [46, 47]), albeit adopting different approaches. The most widely used approaches involve the estimation and utilization of the thermal storage potential of buildings conducting empirical tests (the results of such an approach were used in **Paper II**) and the engineering bottom-up modeling of energy demand in buildings (similar to the approach used in **Papers III–V**). The approach of estimating the potential of space heating DR in buildings based on empirical tests is exemplified by the works of Andersson and Werner [48] and Ingvarsson and Werner [49]. The studies of Kensby [50, 51] have empirically tested the responses of indoor temperature and heat load to different overheating or underheating patterns, concluding that multi-family residential buildings could be utilized as Building Inertia Thermal Energy Storage (BITES) with a capacity of 0.1 kWh/m^2 heated area, given that the indoor temperature deviations from the set-point temperature do not exceed ±0.5°C. The second approach of bottom-up modeling of the energy demand in buildings is exemplified by the work of Reynders et al. [52, 53]. They have proposed a simulation-based quantification method for the characterization of the space heating DR potential from buildings, which is applied to demonstrate the relationship between building properties (e.g., *U*-value) and their flexibility potential for the electric power system. Dreau and Heiselberg [54], Halvgaard et al. [55], and Pedersen et al. [56] have also applied a bottom-up modeling approach to study the thermal behavior and the potential for DR in buildings with electric heating under different control strategies. These studies provide important insights into the potential of buildings to provide flexibility services to the supply side. However, they all share one significant limitation: DR is achieved as a response to a fixed external signal, e.g., an electricity price vector over time. This means that feedback loops from the demand to the supply side are not considered. This limitation can be addressed by interchanging, i.e., soft-linking or hard-linking, calculations of demand and supply, as described below.

Integrated demand-supply modeling of urban heating systems

As mentioned in the *Introduction*, it is important to consider both the demand side and supply side when investigating the development of an energy system. Within the scope of this work, the interlinkage between the energy demand for space heating in buildings and heat generation in DH systems is considered from two perspectives: (i) a long-term investigation of the future, balancing investments in ECMs in buildings and in heat generation/storage technologies in DH systems; and (ii) the impact of elastic demand (DR) on the operation of DH systems. Studies that have explored future developments of the urban heating systems of Frederikshavn in Denmark, Torino in Italy, and Stockholm in Sweden, in which the implementation of ECMs and expansion and modernization of the DH systems were allowed at the same time, have been conducted by Sperling and Möller [57] and Delmastro et al. [58]. Both studies have applied an integrated demand-supply modeling approach and used exogenously defined combinations of demand and supply investments (i.e., limited to a number of possible investment outcomes without optimization). Karlsson et al. [59] have applied the linear optimization model Balmorel, which includes the possibility to invest in ECMs in buildings and in heat generation technologies in DH systems, with the goal of determining if DH systems will be socio-economically attractive in a future, 100% renewable energy system in Denmark. Studies that have applied modeling to study the interactions between DR in buildings and heat generation in DH systems include the works of Pan et al. [60], Gu et al. [61], and Dominikovic et al. [62]. These studies have reported positive effects of the DR from buildings on the operation of DH systems, as reflected in a reduced running cost for heat generation. However, neither of the studies included an explicit accounting for the feedback mechanism between demand and supply manifested as concurrent optimization of space heating demand in buildings and heat generation in DH systems.

In brief, the main limitation associated with most of the above works, as well as with the appended **Papers I** and **II,** is that they do not explicitly account for the feedback loops between demand and supply, which obviously was not the main focus of those studies. This has been a major motivator for the further development of the UC model into an integrated demand-supply optimization model, as applied in **Papers III–V** (further explained in Sections 3.4 and 3.5).

3. Methods and Modeling

The research questions listed in Section 1.1 are addressed by means of a computer-based optimization model, which was developed during the course of this work. This Chapter presents the history of the model development along with the description and motivation for the model modifications made in relation to the posed research questions.

3.1 Overview of the model development

This work is based on the same basic optimization model, albeit with three further developments or adaptations, which are explained in Sections 3.2-3.5. The progression of the model development can be summarized as follows (see Figure 3):

- The first version of the UC model is developed to identify the cost-optimal unit commitment and dispatch of heat generation units available in a DH system (**Paper I**);
- The UCS model takes the UC model as the basis for further refinements that include and investigate the effects of incorporating TES into a DH system (**Paper II**);
- The Energy Balance UC (EBUC) model is developed to integrate the UC model with a building physics energy balance model of a BS, i.e., the EBUC model co-optimizes the space heating demand in buildings with the dispatch of a DH system (**Papers III** and **IV**); and
- The Investment EBUC (invEBUC) model, which is a further development of the EBUC model, includes the possibility to make investments in both demand side (i.e., ECMs in the BS) and supply side (i.e., heat generation and storage) technologies for several model years until mid-century (**Paper V**).

All the models are deterministic, in that the input data are exogenously given in the form of parameters, and all have perfect foresight and a time resolution of 1 hour. The UC, UCS, and EBUC models (**Papers I–IV**) are mixed-integer models, which are developed to minimize the total system running cost of the studied DH system over a time period of 1 year. The invEBUC model (**Paper V**) is a linear programming investment model that has the objective to minimize the total system cost, i.e., the sum of the running cost of the DH system and the costs of investments in both the DH system and in ECMs, over the modeling time horizon. The models are developed using the high-level modeling syntax GAMS [63].

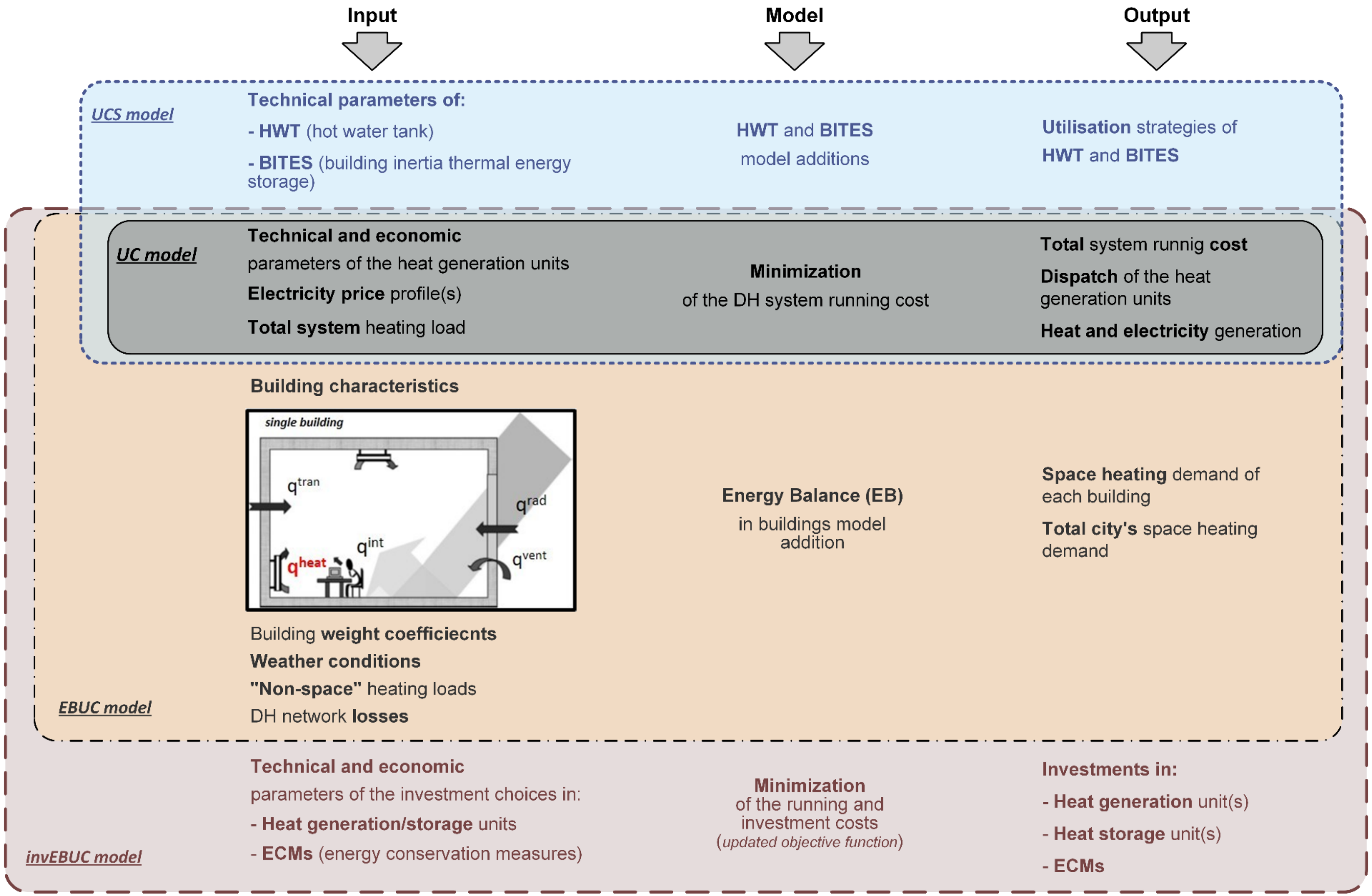

Fig. 3. Schematic of the optimization model and its modifications used in **Papers I–V**. The four rounded rectangles indicate the inputs, modeling features, and outputs included in the first version of the UC model, as well as in the UCS, EBUC, and invEBUC models.

3.2 Unit Commitment (UC) model

In **Paper I**, the implications of future fluctuating electricity prices for the operation of DH systems are investigated. As indicated above, both temporal resolution and timespan are important in these types of studies. Thus, the UC model with a time-step resolution of 1 hour and encompassing a modeling period of up to 1 year was developed. Furthermore, emphasis is placed on the types of benefits that can be obtained through linking the DH system to the power sector, e.g., flexibility services. To address this issue, the UC model is developed as a dispatch model with mixed-integer characteristics and with the main objective of finding the least cost for heat deliveries, while considering the levels of electricity generated by CHP plants and consumed by HPs. An overview of the modeling approach applied in **Paper I** is shown in Figure 3.

The UC model includes detailed technical and economic representations of the heat generation system and is, thus, considered a bottom-up engineering optimization model. Nevertheless, the description of the investigated DH system is limited in the UC model to the parameters of the available heat generation units (Table 1), and no characteristics of the piping network are considered. This is important to remember, as this approach does not account for any congestions that can occur within the network. Furthermore, it is assumed that the investigated DH system has no connections to neighboring DH systems. The parameters of the heat generation units, the applied electricity price profiles, and the total system heating load are given as inputs to the UC model. The mathematical formulation and a detailed explanation of the UC model are available in Appendix A of **Paper I**. The UC model has been validated against real-life data acquired during the operation of the DH system of Gothenburg.

Table 1. The UC model input parameters that characterize the studied DH system (in the present work, the city of Gothenburg).

Description	*Unit*
Max/min output limits of a heat generation unit	kWh/h
Ramp limits of a heat generation unit	kWh/h
Minimum up- and down-times of a heat generation unit	h
Efficiency of a heat generation unit	%
Coefficient of performance (COP) value for HPs	-
Power-to-heat ratio of CHP plants	-
Fuel cost for a heat generation unit	€/kWh
Variable operation and maintenance cost of a heat generation unit	€/kWh
Energy tax	€/kWh
Carbon dioxide tax	€/tCO_2
Price of Electricity Certificates	€/kWh
Start-up cost of a heat generation unit	€

3.3 Unit Commitment with Storage (UCS) model

In **Paper II**, the impact of TES on the operation of DH systems is studied with the help of the UCS model, which is a refinement of the UC model. Two different types of TES are implemented in the UCS model: a centralized HWT (TES via a hot-water tank); and a decentralized BITES (TES via thermal inertia of buildings). Each of the TES options is described in the UCS model using a set of equations that governs the amount of energy stored, the charge and discharge rates, and the energy losses to the surroundings. Since the two storage types are very different in nature – HWT is a supply-side buffer that helps heat generation units to maintain the balance between the supply and demand in every instant, while BITES alters the heating load itself (acts like a DR mechanism) – **Paper II** also investigates the principal differences in their utilization patterns. Figure 3 shows an overview of the modeling approach used in **Paper II**, with the additions made to the UC model highlighted in blue.

The principle of how BITES operates is based on the temporal overheating or underheating of buildings. The description of BITES in **Paper II** is based on the studies of Kensby et al. [50, 51] and Carlsson [64]. Thus, the BITES used in this work consists of two thermal nodes, with one representing the building envelope, i.e., *deep* storage, and the other representing the indoor air and building internals (radiator system, furniture, outer layers of walls), i.e., *shallow* storage. The deep and shallow parts of the BITES, as modeled in the UCS model, are schematically shown in Figure 4. In **Paper II**, the assumption is made that only overheating of buildings is allowed, i.e., a set-point indoor temperature corresponds to an empty BITES and overheating of buildings corresponds to charging of the BITES. The model is limited to only upwards temperature deviations due to the cost minimization (any allowed downregulation in temperature would result in a reduced space heating demand from the buildings and would thereby be an effective energy savings measure) and to reflect the limited discomfort of a sustained increase in the indoor temperature for buildings' inhabitants. The charge and discharge rates of the shallow BITES (this is the part of the BITES that is in contact with the DH network) are dependent upon the outdoor temperature. Energy losses from the shallow and deep parts of the BITES are assumed to decrease linearly in line with decreases in their respective charge levels.

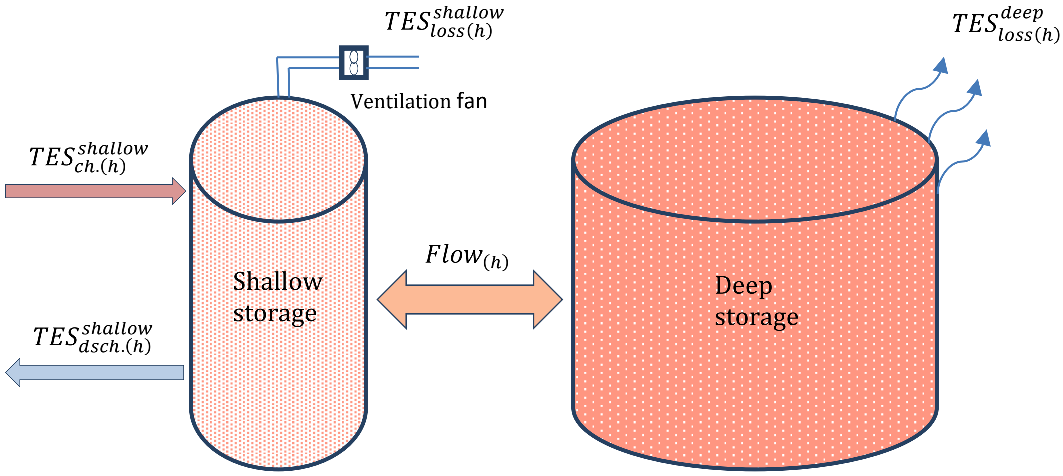

Fig. 4. Schematic of the shallow and deep components of the BITES, as modeled in the UCS model (**Paper II**).

The HWT is modeled as a one-thermal-node storage system under the assumption that the water inside the tank is fully mixed, i.e., that the water temperature inside the tank is uniform. This simplification is justified by the findings of Steen et al. [65], which indicate that the energy losses from a fully mixed TES do not differ significantly from the losses estimated for a TES with ideal stratification (in reality, the stratification that occurs in tanks used as TES is not perfect, mainly due to the mixing of the water that occurs during charge-discharge cycles). Energy losses from the HWT are dependent upon the storage level and the outdoor temperature. More detailed descriptions of the two TES types investigated and the UCS model are given in **Paper II**.

3.4 Energy Balance Unit Commitment (EBUC) model

In **Paper III**, the potential effects of flexible space heating demand (i.e., DR) in buildings on the total system heating load and the operation of DH systems are investigated. **Paper IV** takes this a step further and investigates the effects of space heating DR in buildings and a centralized TES, applied one at a time or at the same time, on the space heating demand in buildings and the operation of the DH system. **Papers III** and **IV** apply the EBUC model adaptation, which was developed by integrating a bottom-up physical space heating demand model of a BS with the basic UC model. The integration of the UC and space heating demand models allowed for explicit accounting of the feedback mechanism between demand and supply, which was both the motivation for and the novelty of **Papers III** and **IV**. Figure 3 includes an overview of the modeling approach used in **Papers III** and **IV** with the modifications made relative to the UC model highlighted in dark gray.

The bottom-up physical space heating demand model of the BS, which is integrated into the EBUC model, originates from the Energy Carbon and Cost Assessment of BS (ECCABS) model by Mata et al. [66], and subsequently developed further by Nyholm et al. [67]. In brief, the space heating demand model of the BS calculates the space heating demand required to maintain indoor temperatures within given limits for each modeled building based on its physical properties, climate conditions, and the heating gains/losses that occur in the buildings (Table 2). The calculation of heat transfers to/from the buildings due to ventilation and transmission are based on the indoor air temperatures in the buildings. Each modeled building is represented by one external thermal zone, i.e., the building envelope, and one internal thermal zone that includes the indoor air, furniture, and surface layers of the internal walls. The calculated space heating demand of each modeled representative building is extrapolated to the overall space heating demand of the entire BS using BS weight coefficients from the description of the BS. Thus, the EBUC model estimates the space heating demand endogenously in the model and, at the same time, calculates the optimal dispatch of the supply, i.e., includes a feedback mechanism between the demand and supply. The space heating DR from buildings is in the EBUC model realized by allowing for indoor temperature deviations from the set-point value. As a result, the space heating demand in the buildings can be shifted in time as long as the indoor air temperature remains within the predefined temperature range. More detailed descriptions of the modeling methodology and the EBUC model can be found in **Papers III** and **IV**.

Table 2. EBUC model input parameters that characterize the investigated BS.

Description	*Unit*
Total heated floor area of a building	m^2
Total area of the external surfaces of a building	m^2
Total area of the window surfaces of a building	m^2
Shading coefficient of windows	-
Frame coefficient of windows	-
Coefficient of solar transmission through windows	-
Average U-value of a building	kW/m^2·°C
Thermal mass of the external thermal zone	kW/°C
Thermal mass of the internal thermal zone	kW/°C
Solar irradiation	kW/m^2
Outdoor temperature	°C
Average constant values of the heat gains due to: - fan work, lighting, electrical appliances and occupants	kW/m^2
Hourly profiles of the heat gains due to: - fan work, lighting, electrical appliances and occupants	-
Efficiency of a heat recovery system (if available)	%

Importantly, in **Paper III**, the space heating DR potential from the investigated BS is tempered by the assumption that the temperature of the buildings can only increase above the set-point requirement. This assumption is, once again, due to the cost-minimizing nature of the EBUC model. If the temperature was allowed to drop below the set-point value, the model would obviously exploit this possibility to decrease the heat supply and, thereby, reduce the total system running cost. While this would represent an energy-saving measure, the focus in **Paper III** was on the DR potential from buildings. It should also be noted that the capacity of the BITES in **Paper II** was also estimated by allowing for upward deviations of the indoor air temperature in the buildings. However, the explicit modeling of the space heating demand from buildings enabled in the EBUC model, as compared to the representation of the thermal mass of the buildings as TES in the UCS model, enhances our understanding of the factors that drive the actual demand. This raises new research questions in relation to the DR and/or energy efficiency measures in buildings.

In **Paper IV**, the possibility for downregulation of the temperature in buildings is allowed, together with the possibility for upregulation of the temperature to study both the space heating DR (upregulation) and the potential for energy savings (downregulation) from buildings. However, in **Paper IV**, the general decrease in heat supply was avoided by having different allowed temperature limits throughout the day.

3.5 Investment Energy Balance Unit Commitment (invEBUC) model

Paper V investigates the cost-optimal mix of a reduction in space heating demand in buildings, via investments in ECMs, and investments in the DH system. The invEBUC model applied in **Paper V** uses the EBUC model, which makes it possible to make investments in both demand-side and supply-side technologies. Figure 3 shows an overview of the modeling approach used in **Paper V**, with modifications made relative to the EBUC model highlighted in brown.

The objective function of the invEBUC model is to minimize the total system cost, which constitutes the running cost of the DH system (as in the reference EBUC model) and the cost for investments in both the DH system and in ECMs in the BS over the modeling time horizon. The time horizon of the model is 2020–2050 with a 10-year step allowing for investments from Year 2030 and onwards (the existing BS and heat generation technologies are modeled for Year 2020). Thus, the invEBUC model identifies the cost-optimal combination of future investments in DH technologies and ECMs applied to buildings, while satisfying the hourly demand-supply balance for each of the modeled years. The ECMs and DH technologies available as investment choices in the invEBUC model and analyzed in this work are listed in **Paper V**.

It should be noted that the two-node representation of the buildings in the original EBUC model is simplified in the invEBUC to a single-node representation. This is to avoid non-linearity of the invEBUC model. For this reason, the calculation of heat transfers to/from buildings due to ventilation is based on the indoor air temperature, while the indoor operative[1] temperature is used to calculate heat transfers due to transmission. It should also be noted that the binary variables used in the original EBUC model to represent the technical limitations of the heat generation units (minimum heat output level and start-up characteristics) are removed, and that the representation of such units are, in the invEBUC model, linearized to reduce calculation times. This linearization is achieved via a so-called *two-variable approach*, with one variable indicating the hourly generation and one variable indicating the spinning capacity available for the generation of heat/electricity (inspired by the work of Göransson [68]). **Paper V** provides a more detailed description of the invEBUC model, with an in-depth description of the approach developed to model investments in ECMs in buildings, as well as the technical and economic parameters of the applied ECMs and DH technologies.

3.5 Definitions and indicators

As indicated in Section 1, one of the main challenges associated with the operation of DH systems is the variable heating load, in both the short-term (daily) and long-term (seasonal) perspectives. To obtain a sense of the heat-load variations on different time-scales, the terms *relative daily load variations* (**RDLV**) [31] and *relative weekly load variations* (**RWLV**) are introduced.

RDLV and **RWLV** are defined as follows:

$$\boldsymbol{RDLV} = \frac{{}^{1}/_{2} \cdot \sum_{h=1}^{24} |Tot.Load_h - Tot.Load_d|}{Tot.Load_{yr} \cdot 24} \tag{1}$$

$$\boldsymbol{RWLV} = \frac{{}^{1}/_{2} \cdot \sum_{h=1}^{24\cdot 7} |Tot.Load_h - Tot.Load_w|}{Tot.Load_{yr} \cdot 24 \cdot 7} \tag{2}$$

where $Tot.Load_h$, $Tot.Load_d$, $Tot.Load_w$, and $Tot.Load_{yr}$ are the average system heating loads of the studied system over hours, days, weeks and a full year, respectively. The **RDLV** and **RWLV** values are determined for each day and for each week of the year, respectively, and quantify the amounts of heat that are averted from the daily average and weekly average heating loads. In other words, the **RDLV** and **RWLV** reflect the extents to which the hourly values of the heating load diverge from the daily average and weekly average values, respectively.

[1] Operative temperature is defined as an average of the air temperature and the average radiant temperature from surrounding surfaces [83].

4. Input data

This chapter describes the data inputs used in this thesis and in the appended papers. The City of Gothenburg, Sweden is taken as a case study in all the papers. Thus, the data concerning the investigated DH system, the BS, and the local weather conditions are for Gothenburg. The data described in this thesis and the appended papers are for Year 2012, unless stated otherwise.

4.1 District heating system

As indicated in Section 3.2, the investigated DH system is represented by a limited set of technical and economic parameters for the heat generation and storage units. However, depending on the scopes of the different papers and the posed research questions, specific assumptions and the availabilities of units differ between the studies. As Table 3 shows, only the heat generation units that are currently available in the DH system are modeled in **Papers I–III**. In **Paper V**, the heat generation mix of the DH system in Year 2020 is assumed to be limited to the existing units, whilst in the period 2030–2050 investments in new heat generation and storage units are allowed. **Paper IV** studies the effects of DR from buildings and TES for the operation of the DH system in Year 2050 and thus, applies the heat generation capacity mix derived for that year from the study in **Paper V**. Centralized TES is available in the studied DH system in **Papers II**, **IV**, and **V**. However, the capacity of the centralized TES in **Paper II** is assumed to match the capacity of the BITES, whereas the capacities of the TES systems in **Papers IV** and **V** are a result of the invEBUC model optimization.

Table 3. Indications of the availabilities and types of heat generation and storage units used in the appended papers. The symbol × indicates that the feature has been used in the designated paper.

	Paper I	Paper II	Paper III	Paper IV	Paper V
Existing heat generation units	×	×	×		×
New (invested in) heat generation units				×	×
Centralized TES		×		×	×

The technical parameters of the existing heat generation units in the DH system are mainly taken from the environmental reports (*miljörapporter*) issued yearly by the DH system operator, which describe the operation of the heat generation units during the year (exemplified by [69, 70]). The hourly values of the supply and return water temperatures in the DH network are provided by the DH system operator. The economic parameters of the heat generation units used in **Papers I–III** (modeling year: 2012) and for Year 2020 in **Paper V** are extracted from a number of governmental or scientific reports, as given in the specific papers. The prices for wood chips, wood pellets, and fuel oil are obtained from the Swedish

Energy Agency [71]. The prices for bio oil and natural gas are assumed based on the information in the purchase contracts. The energy and carbon taxes are taken from the Swedish Tax Agency [72]. The prices for Electricity Certificates, which are designed to support renewable electricity generation in the Nordic countries, are also obtained from the Swedish Energy Agency [73]. The data on the operation and maintenance costs are those confirmed by the DH system operator.

The technical and economic parameters of the heat generation and storage units available as investment choices in **Paper V** and indicated as being available in the DH system in **Paper IV** are mainly taken from the report issued by the Danish Energy Agency [74]. The biomass prices used for the period 2030–2050 in **Paper V** are extracted from the study of Hagberg et al. [75].

4.2 Heating load

The data on the total system heating load, used as inputs in **Papers I–II**, are extracted from the real-life records of the operation of the investigated DH system. The total system heating load data set represents the aggregated heat generation from the heat generation units available within the system. However, the aggregated heat output from the generation units is assumed to be equal to the total system heating load, i.e., the level of heat generation that meets the load requirement. The non-space heating load, which is assumed to consist of the hot-water and industrial heating loads, applied in **Papers III–V**, is obtained by disaggregation of the real-life measured generation in Year 2012 (described in detail in **Paper III**).

4.3 Building stock

In **Papers III–V**, a description of the Gothenburg BS, consisting of 134 representative buildings, is applied in the modeling and is based on the descriptions of the buildings in the BETSI (*Byggnader Energi, Tekniska Status och Inomhusmiljö*) database [76]. The BETSI database contains detailed description of 1,800 buildings, which were chosen by *Boverket* [77] and Statistics Sweden [78] as being representative of the standing Swedish BS in Year 2005. The representative residential buildings – Single-Family Dwellings (SFDs) and MFDs – are chosen by matching the locations of the sample buildings in BETSI to their locations in the city of Gothenburg, and by choosing buildings that are indicated as being connected to DH. Additional archetype residential buildings were created to represent the buildings constructed under the period 2005–2012.

The non-residential BS connected to the DH system of Gothenburg is represented by 40 archetype Non-Residential Buildings (NRBs). This number is obtained by having one archetype building for each building type in each construction period, as indicated in Table 4. The non-residential building types and construction periods were originally identified by the Swedish Energy Agency [79], and subsequently aggregated (from the original 13 types) into five types based on the aggregations used in the BETSI report [76].

Table 4. The building types and construction periods used to obtain representative non-residential buildings (NRBs), which represent the non-residential building stock (BS) of Gothenburg, i.e., each building type exists for each period, yielding a total of 40 NRB types.

Building type	Construction period
1. Hotels, restaurants,	–1940
office/administration, food commerce,	1941–1960
other commercial	1961–1970
2. Healthcare 24/7, other healthcare	1971–1980
3. Educational	1981–1990
4. Dwellings*, religious, garages	1991–2000
5. Sports centers, cultural, other	2001–2010
	2010–

* *Apartment buildings in which the majority of the area is used for non-residential purposes.*

The national BS weight coefficients, i.e., the coefficients used to scale up the chosen representative buildings to represent the total BS of Gothenburg, for SFDs and MFDs are also based on data from BETSI. The data for the year of construction (available in [78]) and for the number of residential buildings connected to the DH system of Gothenburg (90% of MFDs and 20% of SFDs, according to the DH system operator [80]) are used to recalculate the national BS weight coefficients of MFDs and SFDs, so as to represent the residential BS of Gothenburg in **Papers III–V**. The national BS weight coefficients for NRBs are derived from the available statistics on the total number and the total heated floor area of NRBs in Sweden, as published by the Swedish Energy Agency [79]. The data on the total heated floor area of NRBs located in the Västra Götaland Region, in which Gothenburg is located, and the numbers of residents living in the region [78] and in the city are used to recalculate the national BS weight coefficients to the coefficients that are applied to the non-residential BS of Gothenburg. **Paper III** gives more detailed information on how the data describing the representative buildings and their respective weight coefficients were collected and handled.

The variations in the internal heat gains from lighting, appliances and occupants in the modeled representative buildings are given as inputs to the EBUC and invEBUC models in **Papers III–V**. The internal heat gain profiles for SFDs and MFDs are taken from the study of Nyholm et al. [81]. The profiles for NRBs are extracted from the work of Grundsell [82].

4.4 Indoor temperature in buildings

As indicated in Section 3, both indoor air and indoor operative temperatures are used in the appended papers to calculate the energy balances over the modeled buildings. The indoor operative set-point temperatures in the MFDs, SFDs, and NRBs are set to 21°C, 20°C, and 20°C

(22°C in educational NRBs (edNRBs) in **Papers IV** and **V**), respectively, which are within the recommended operative temperature interval of 20°–23°C [83, 84]. The set-point temperature in MFDs is higher than in SFDs due to the assumption that most of the apartments are rentals and are obliged to comply with the contractual temperature of 21°C [83], while SFDs are owned by the residents and have the set-point temperature at the lowest allowed value. The indoor air set-point temperatures are set to be higher than the operative temperatures by 1.5°C, i.e., 22.5°C, 21.5°C, and 21.5°C (23.5°C in educational NRBs in **Papers IV** and **V**), respectively, based on the findings reported elsewhere [83, 85].

In **Paper III**, the indoor air temperature in buildings is allowed to deviate, although only upwards from the set-point by 1°C and 3°C, depending on the modeled scenario. The limit on the upward deviation of the temperature in buildings in **Paper IV** is set at 3°C. The maximum limit of 3°C is based on the recommended indoor temperature comfort ranges for living spaces, according to the ISO Standard for Ergonomics of the Thermal Environment [86], and for office environments, according to the American Society of Heating and Refrigerating and Air Conditioning Engineers (ASHRAE) (summarized in [87]). In the scenarios that allow the indoor air temperature in buildings to decrease (**Paper IV**), the permitted decreases in temperature are limited by predefined profiles. Figure 5 shows the lower boundaries of the allowed indoor air temperature deviations in the SFDs, MFDs, NRBs, and edNRBs, respectively. It is assumed that all the building types can go down in temperature during the night-time, while only the SFDs and MFDs can reduce their indoor air temperature to 19.5°C during the day-time on workdays.

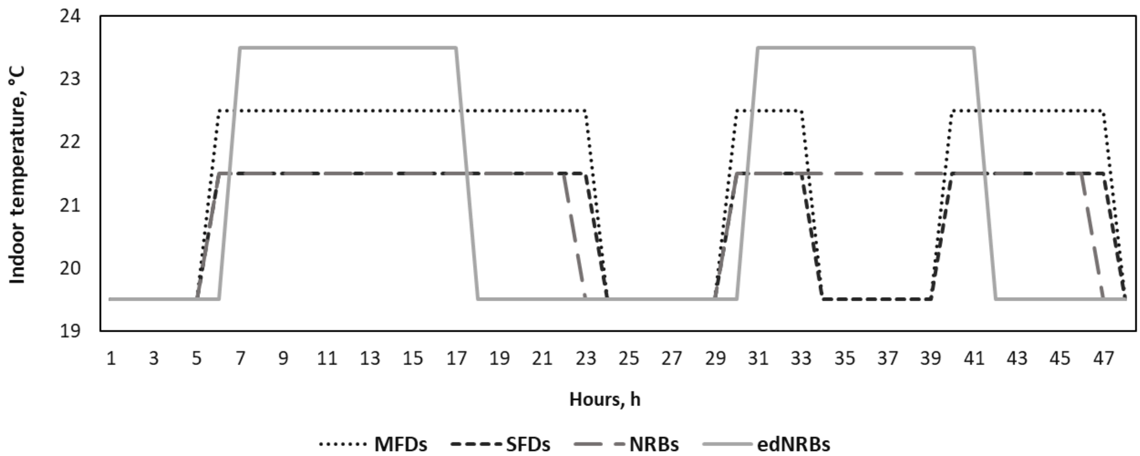

Fig. 5. The lower boundaries of the allowed indoor air temperature deviations in the building types included in the modeling of **Paper IV**: MFDs, SFDs, NRBs, and edNRBs, as illustrated for a 2-day period (weekend and weekday).

4.5 Electricity prices

Two types of electricity prices are used in the appended papers: historical wholesale prices and modeled prices. **Papers II** and **III** use the historical wholesale day-ahead electricity price profile for Year 2012, as extracted from the Nordic Electricity Market – Nordpool [88]. The same price profile is used for Year 2020 in **Paper V**, since applying a more recent electricity profile would require that other input data be updated accordingly, e.g., to the corresponding outdoor temperature and solar irradiation profiles. The future electricity price profiles used in **Papers I** and **IV** and for the period 2030–2050 in **Paper V** are extracted from the ELIN-EPOD modeling package. The ELIN model is an investment optimization model that computes the development of the European (EU-27 Member States plus Switzerland and Norway) electricity system up to Year 2050. The ELIN model scenario results are transmitted to the dispatch EPOD model for further analysis at a higher time-resolution. More detailed information on the ELIN-EPOD modeling package is available elsewhere [89, 90]. The prices of Electricity Certificates for the period 2030–2050 in **Paper V** and in **Paper IV** (Year 2050) are also derived from the ELIN-EPOD modeling package.

4.6 Weather data

Data for the outdoor temperature are used in **Papers II–V**. The dataset consists of the hourly values averaged from the measurements collected by six temperature sensors located throughout the city of Gothenburg. In **Papers III–V**, these data are used for calculating the heat gains/losses in the investigated BS due to air ventilation and energy transfer between the building structure and the surroundings. In **Paper II**, the outdoor air temperature is used to calculate the energy losses from the hot-water tank and to identify the maximum charge/discharge rates for BITES.

Solar irradiation data, which are used in **Papers III–V** for the calculation of the heat gains in the BS due to solar irradiation, were obtained from the Swedish Meteorological and Hydrological Institute [91]. The dataset used contains the solar irradiance level for the Nordic countries and has a spatial resolution of 11 × 11 km and a temporal resolution of 1 hour.

5. Results and Discussion

This chapter, which presents the key results and generic insights from the appended papers, is divided into three sections. Section 5.1 concerns the future development of urban heating systems, with special attention paid to the balancing of reductions in the energy demand from buildings and transformation of the heat generation side - DH systems. Section 5.2 discusses the impacts of activating space heating DR in buildings on the indoor environment and the operation of DH systems. Differences in impacts from DR in buildings compared to those from centralized TES systems are discussed in Section 5.3. In Section 5.4, the interplays between the heat generation in DH systems and the power sector are investigated.

5.1 Reducing the demand or transforming the supply

As mentioned earlier, reducing the energy demand of the building sector can confer substantial environmental benefits and is, therefore, one of the essential components of the global development. With DH systems already acting as a major heat supplier in many countries, it is of great importance that both the demand and supply sides are considered when identifying the most socio-economically beneficial system that fulfils the list of requirements. Our results show that from the cost-minimizing “social planner” perspective, the optimal development of urban heating systems will require improvements to the energy performances of buildings, as well as the transformation of DH systems. However, the extent of the transformation of both sides may be affected by the types of requirements and demands that are imposed via external factors, e.g., efficiency improvement targets. The energy efficiency improvement targets investigated herein, introduced as internalized externalities, come at a higher system cost but result in greater investments in ECMs and, thus, greater energy savings, than the scenario without targets.

The results of the modeling in **Paper V** reveal that the least-cost development scenario for the studied urban heating system of Gothenburg is achieved through investments in ECMs in buildings, in combination with investments in heat generation and storage technologies in the DH system. Figure 6 shows that in the *Reference* scenario, which is the scenario in which only fuel and electricity price developments drive demand reductions (no external targets are set), investments in ECMs lead to space heating demand savings of around 25% by Year 2030. It is also evident that there is little additional investment in ECMs in the 2040 and 2050. These savings are mainly attributed to the installation of ventilation heat recovery systems in MFDs and NRBs (buildings that, in contrast to SFDs, have high ratios of heated floor area to external surface area) and to the insulation of roofs. It is noteworthy that the insulation of roofs is the only envelope ECM implemented in the *Reference* scenario. However, it should be remembered that the applied optimization-based methodology prioritizes ECMs based on cost per unit of saved energy and disregards the willingness of different homeowners to pay for the ECMs. Thus, it should not be readily assumed that the insulation of roofs is the only type of envelope ECMs expected in the future. Nevertheless, these results reflect the economically feasible threshold of investments in ECMs, given the future energy cost projections, from the perspective of the local heating system.

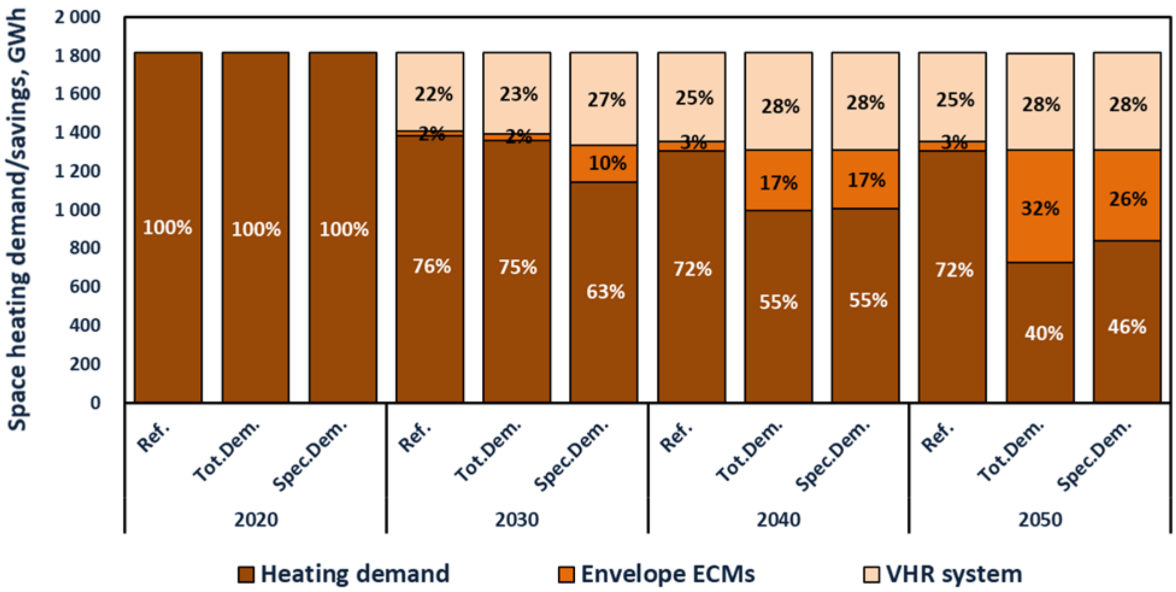

Fig. 6. Space heating demand and space heating demand savings in the studied building stock of Gothenburg in the period 2020–2050, as obtained using the invEBUC model for the *Reference*, *Tot.Dem.*, and *Spec.Dem.* scenarios. Source: **Paper V**.

The results indicate that a combination of HPs, electric boilers, and pit TES reflects cost-optimal generation and storage capacity by Year 2050 (*cf.* Figure 7). The size of the pit TES suggested for investment reaches 100 GWh and serves as both long-term (seasonal) storage (storing heating energy from summer to winter) and short-/medium-term storage (further reflected upon in Section 5.3.2). The availability of such a large TES is the main reason that most of the heating energy in Year 2050 will still be provided by the industrial waste heat sources and municipal waste incineration plant, which is clearly a case-specific result for the studied DH system. Nevertheless, our results provide an important insight for other DH systems that do not possess significant waste heat resources, in demonstrating that a combination of electricity-consuming heat generation technologies and a TES can be a cost-effective future heating solution.

Obviously, the relationship between the future fuel (in this work, biomass) and electricity prices will influence the types of heat generation technologies that will attract investment in DH systems. To test this hypothesis, in **Paper V**, an additional model run with setup identical to the *Reference* scenario but with lower future biomass prices was performed. The results of that model run reveal that the future cost-optimal heat generation capacity mix of the studied DH system entails investments in CHP plants rather than in HPs (for more details, see **Paper V**). In addition, our results from **Paper I** indicate that both the average electricity price and the price fluctuations affect the dispatch and operational strategies of CHP plants and HPs, if both of these technologies are available in a DH system. The results show that CHP plants are prioritized to operate and maximize electricity generation during periods of high electricity prices, while HPs are operated during periods of low electricity prices. Reflecting on the results from **Papers I** and **V**, it appears that neither of these technologies can be chosen as the ultimate heat generation technology for the future. Instead, a combination of CHP plants, HPs, electric boilers (for short-term peaking operation), and TES systems, all operated through a smart control system, is likely to ensure the most beneficial centralized heat supply (centralized, since individual heating applications are not included in this reflection).

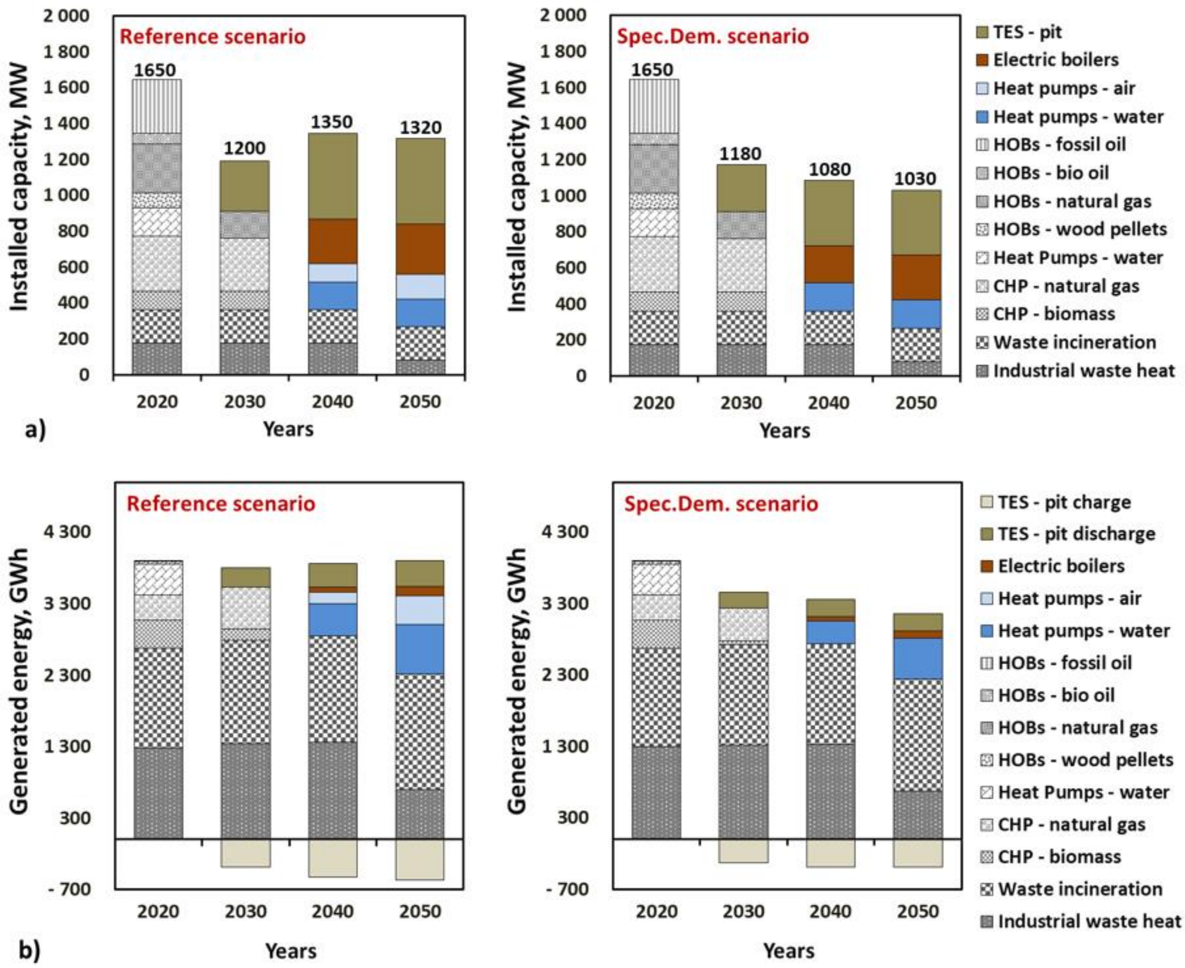

Fig. 7. Installed capacity (a) and generated (charged/discharged for TES) heat (b) from the heat generation/storage technologies in the district heating system of Gothenburg in the period 2020–2050, as obtained through invEBUC modeling of the *Reference* and *Spec.Dem.* scenarios. Source: **Paper V**.

Even though the aforementioned space heating demand savings of around 25% would be a significant achievement for the building sector, several (e.g., global, national, sectoral) established energy demand reduction targets require even greater improvements in the energy performance of buildings. In **Paper V**, two energy demand reduction targets were set (one at a time) for the investigated BS of Gothenburg: (i) the total demand reduction (*Tot.Dem.* scenario) target for the entire BS, which should reflect the EU's energy efficiency ambition level[2]; and (ii) the specific demand reduction (*Spec.Dem.* scenario) target, which prescribes specific energy use (in kWh/(m^2·y)) for each building individually and reflects the Swedish energy efficiency ambition level[3]. Naturally, setting any of these targets resulted in a higher implementation rate of ECMs in the buildings, as compared to the scenario with no targets. However, the ways in which the targets are met and the costs of their implementation are different.

Figure 6 shows that space heating demand savings of up to 60% (targeted value) and 54% (model result) are achieved in the *Tot.Dem.* and *Spec.Dem.* scenarios, respectively, by Year 2050, as compared to Year 2020. In both of these scenarios, investments in ventilation heat recovery systems are made in all building types and result in significant energy savings by Year 2050, supporting the cost-effectiveness of this ECM type. Setting up a demand reduction target also results in the implementation of all the envelope ECM types, i.e., insulation of roofs and walls and replacement of windows, as compared to the scenario with no target and only a small fraction of the roofs being insulated. However, the extent of implementation and the prioritization of ECMs throughout the investment periods are different. The modeling results show superior economic feasibility linked to the insulation of roofs, as compared to the insulation of walls and replacement of windows. It is also observed that the *Spec.Dem.* scenario differs from the *Tot.Dem.* scenario in having significantly larger investments in all three types of envelope ECMs already by Year 2030, i.e., there are greater investments in the short term in the *Spec.Dem.* scenario. This is because buildings need to comply with the specific space heating demand reduction target individually. Thus, buildings with currently high specific space heating demand (in the BS of Gothenburg these are mainly SFDs) require heavy investments in ECMs in the short term in order to meet the target. In addition, the results indicate that the present net value of the total investment cost (both demand-side and supply-side investments) is 10% higher in the *Spec.Dem.* scenario than in the *Tot.Dem.* scenario. Therefore, meeting the Swedish target will require more intensive efforts (e.g.,

[2] The *Tot.Dem.* scenario prescribes reduction targets for the total space heating demand in the investigated BS, which should decrease by 25%, 45%, and 60% by Years 2030, 2040, and 2050, respectively, as compared to Year 2020. The 60% demand reduction level by Year 2050 reflects the average renovation rate of buildings of 3% annually indicated in EPBD [3].

[3] The *Spec.Dem.* scenario prescribes that the specific space heating demand be <55 kWh/(m^2·y), <45 kWh/(m^2·y), and <35 kWh/(m^2·y), by Years 2030, 2040, and 2050, respectively, for each building individually. The target for Year 2030 is based on the Swedish building renovation strategy [97, 98], while the targets for Year 2040 and Year 2050 are set to achieve "deep renovation" of buildings by Year 2050 [99].

stricter policies, more subsidies) in the near-term future and greater overall investments in the period up to Year 2050 than will meeting the European target, while the final outcome in terms of the reduced energy demand for space heating is shown to be similar. This shows that policies that target total energy use reductions have the potential to achieve the same energy savings at a lower cost than policies that are focused exclusively on the specific energy use in buildings.

From Figure 7, it can be deduced that both the installed capacity and the amount of generated heat are lower in the *Spec.Dem.* scenario (and in the *Tot.Dem.* scenario), as compared to the *Reference* scenario, and this is obviously due to the significantly lower space heating demands in the scenarios with the demand reduction targets. If one assumes that in the future all buildings will be required to become zero-energy buildings, the future of DH systems looks uncertain. However, even if the demand for space heating drops to zero, the demand for hot-water supply is likely to increase in the future, since more buildings are being built to meet increasing urbanization. The competitiveness of DH systems is also expected to remain high in the future, due to low distribution capital costs in densely populated cities [92]. Furthermore, new sources of waste heat, e.g., biomass refineries and data centers, make a strong case for continuing to use DH systems so as to prevent wastage of available resources.

The results of the modeling also show that the investments in ECMs significantly improve the energy performance of the buildings. Figure 8 shows the distribution of the total heated floor area of the BS of Gothenburg across the ranges of specific space heating demand in the *Reference* and *Tot.Dem.* scenarios. In the *Tot.Dem.* scenario, up to 82% of the total heated floor area of the investigated BS has a specific space heating demand of <35 kWh/(m^2·y) by Year 2050. In the *Spec.Dem.* scenario, the target for all the buildings in Year 2050 is set with a specific space heating demand of <35 kWh/(m^2·y). These results indicate that in both scenarios with space heating demand reduction targets, the majority of the buildings in the city will be characterized as low-energy buildings by Year 2050.

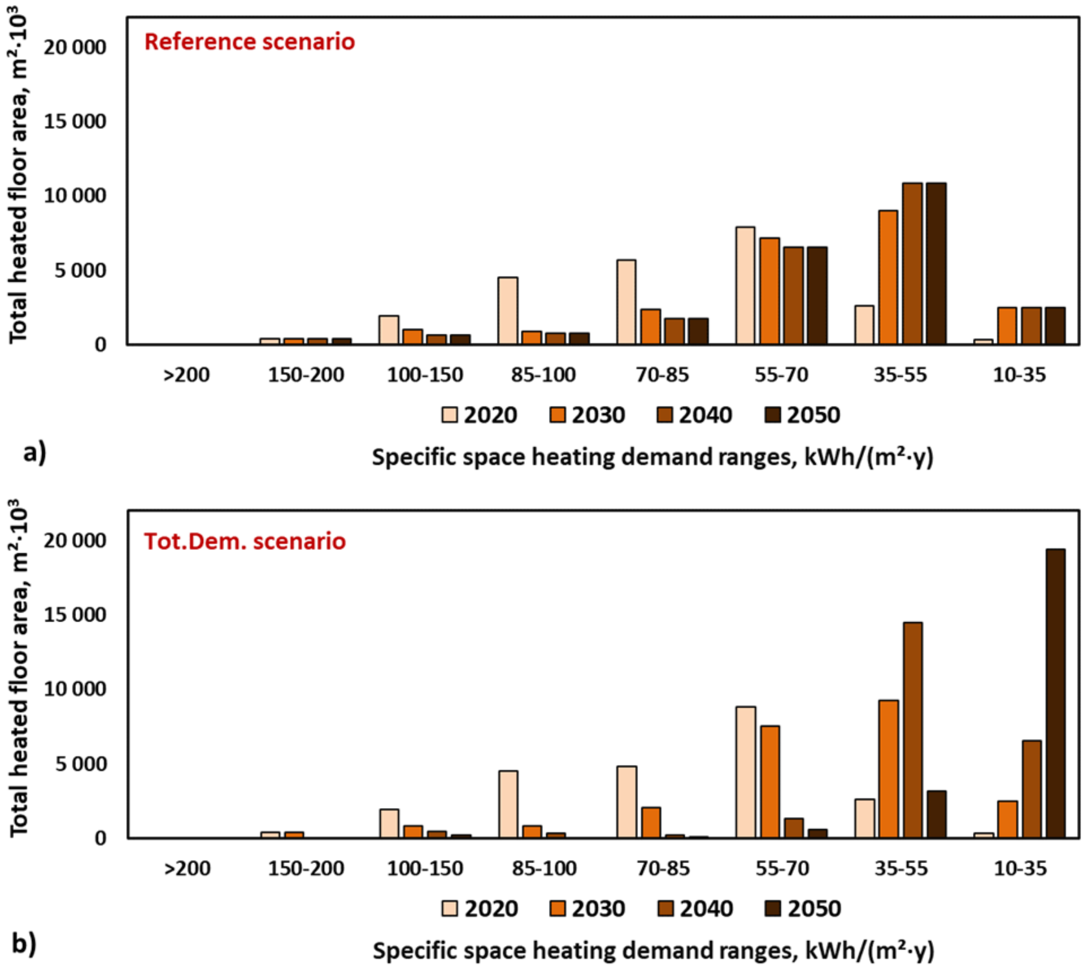

Fig. 8. Total heated floor area of the BS of Gothenburg categorized according to the specific space heating demand ranges in the (a) *Reference* and (b) *Tot.Dem.* scenarios. Source: **Paper V**.

It is also apparent that in the *Spec.Dem.* scenario some buildings are not able to comply with the Swedish target, even with all the available ECM types being implemented (for further details, see **Paper V**). An obvious way to meet the target is to consider more ECM types with better energy performance characteristics for implementation in buildings. Whilst this is a viable solution, it would obviously come at great cost. An alternative/supplementary way to reduce the energy demand for space heating in buildings is to reduce the indoor temperature in buildings, e.g., for residential buildings, during the night-time or when people are at work. This solution would require investments in smart control systems, although this cost could be attributed (at least in part) to activated DR in buildings, the benefits of which are discussed below.

5.2 Demand- and supply-side flexibilities in DH systems

5.2.1 The effects of space heating demand flexibility on the operation of buildings and the total system heating load

The results from the modeling in **Papers III–IV** show that activated DR in the buildings can effectively benefit the studied DH system by moderating the heat load variations and reducing the total cost of heat generation. Figure 9 exemplifies the hourly indoor air temperature and hourly space heating demand averaged over the representative MFDs in the *Ref.* and *Tup* scenarios, as obtained through the EBUC modeling in **Paper IV** (modeled for Year 2050) and presented for 4 days in February. The figure also shows the total system's heating load curve, divided into network losses, non-space heating load, and space heating load from the buildings, designated as *not moved*, *increased*, or *decreased* in the *Tup* scenario, as compared to the *Ref.* scenario, during the same period. The presented scenarios differ in that in the *Ref.* scenario, no active DR is allowed in the investigated buildings, i.e., the space heating demand is calculated with the objective of maintaining the indoor air temperature in the buildings at a set-point value. However, the indoor air temperature is not prevented from increasing above the set-point value due to the influences of, for example, the outdoor air temperature, solar irradiation, and internal heat gains. In the *Tup* scenario, DR achieved through upward temperature deviations of up to 3°C is allowed.

From Figure 9, it is clear that there are hours during which the heat generation in the *Tup* scenario exceeds the level of heat generation in the *Ref.* scenario. During these hours, the average indoor temperature of the investigated MFDs in the *Tup* scenario is also higher than that in the *Ref.* scenario, i.e., the thermal energy is stored. Likewise, there are hours when the level of heat generation in the *Tup* scenario is lower than that in the *Ref.* scenario. During these hours, the thermal energy stored from the previous hours of overheating is used, and the indoor temperature of the buildings decreases simultaneously. Such active oversupply of heating energy to buildings followed by undersupply of heating energy constitutes a DR event. The DR event exemplified in Figure 9 between Hour 33 and Hour 90 is activated in response to a "signal", in this case the change in electricity price, with the goal of optimizing the heat generation in the DH system. During Hours 33–71 in Figure 9c (hours with low electricity prices), the total system heating load in the *Tup* scenario is larger than that in the *Ref.* scenario (thermal energy is stored), being 420 MWh/h. This level of load corresponds to the maximum total heat outputs from the base-load, waste-based, heat generation units and the sewage water-based HP, for the majority of the hours. During Hours 72–90, which are characterized by significantly higher electricity prices, the heating load in the *Tup* scenario is lower than that in the *Ref.* scenario (thermal energy is released). This, in turn, results in decreased output of the sewage water-based HP during these hours and, correspondingly, a reduced cost for heat generation.

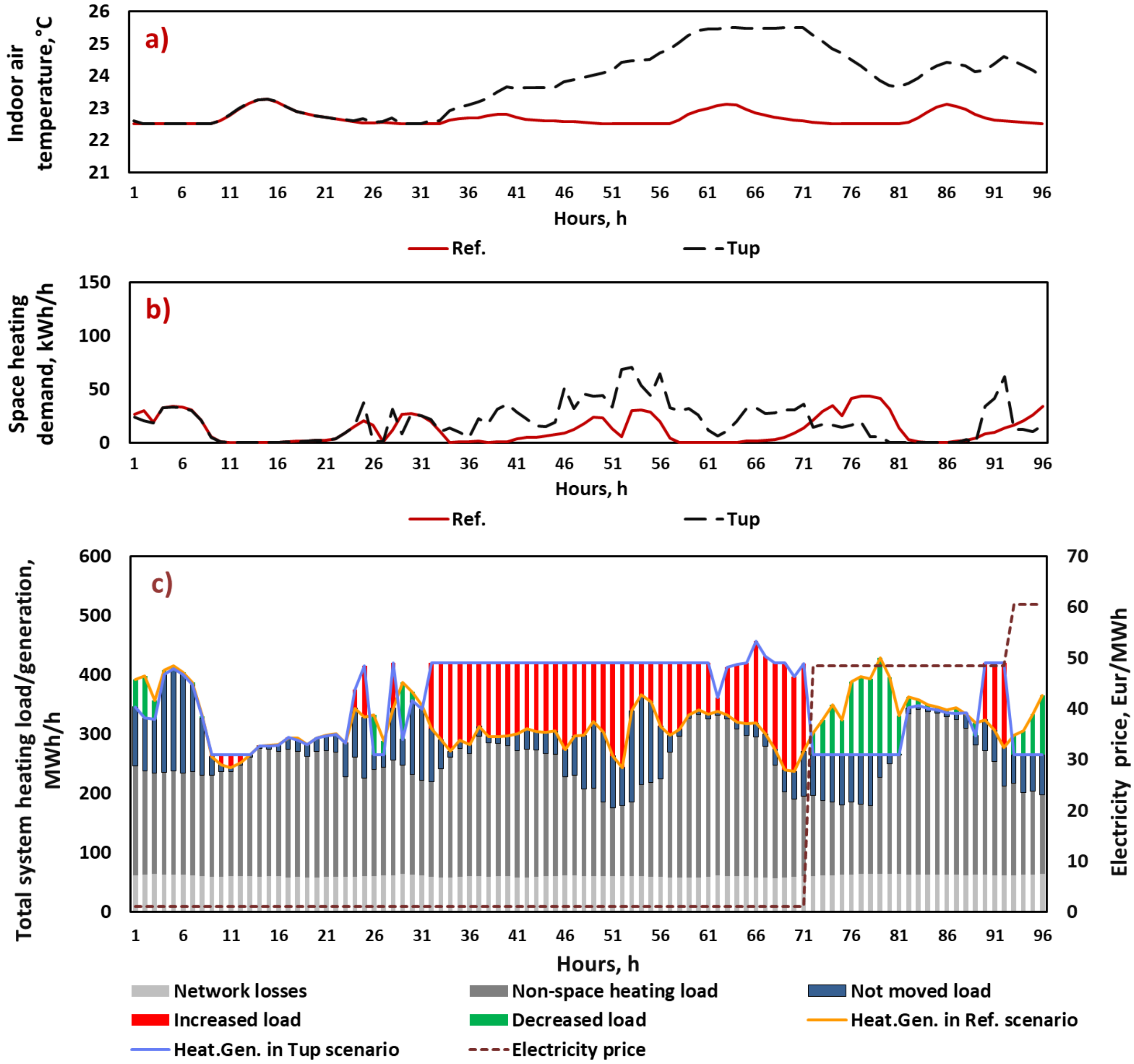

Fig. 9. The hourly indoor air temperature (a) and hourly space heating demand (b) averaged over the representative MFDs in the *Ref.* and *Tup* scenarios, together with the total system heating load (c), divided into network losses, non-space heating load, and *not moved*, *increased*, and *decreased* space heating load in the *Tup* scenario, as compared to the *Ref.* scenario. Data obtained through the EBUC modeling and presented for 4 days in February. Figure is based on the results from **Paper IV**.

The results from **Paper IV** show that the total shifted space heating load over the modeled period (one year, excluding the period from May 15th to September 15th) in the *Tup* scenario was 172 GWh, as compared to the *Ref.* scenario. This value corresponds to 9% of the total yearly system (city's) heating load. The maximum hourly value of space heating load shifted for the purpose of "peak shaving" was 233 MWh/h, which corresponds to 33% of the highest hourly heating load in the *Ref.* scenario. The highest value of the shifted load for "valley filling" was 318 MWh/h.

The results from **Paper III** show similar effects of activated DR in the current BS of Gothenburg on the DH system as of Year 2012. The total shifted space heating load over the modeled period (one year without the period from May 15th to September 15th) in the *DR 3°C* scenario (identical to the *Tup* scenario described above for **Paper IV**) was 226 GWh, as compared to the *Ref.* scenario (no DR). This value corresponds to 7% of the total yearly system (city's) heating load. The maximum hourly value of the space heating load shifted for the purpose of "peak shaving" was 213 MWh/h, which corresponds to 20% of the highest hourly heating load in the *Ref.* scenario.

It is noteworthy that the relative values of the total shifted space heating load and the maximum hourly space heating load shifted for the purpose of "peak shaving" are lower in **Paper III** (Year 2012) than in **Paper IV** (Year 2050), i.e., 7% and 20% compared to 9% and 22%, respectively. These differences can be attributed to various causes, e.g., different electricity price profiles and different heat generation units available in the DH system. However, one of the main reasons should be that the modeled BS in Year 2050 (**Paper IV**) has undergone energy refurbishments (as indicated in Section 5.1) and, on average, has a lower *U*-value and higher heat-recovery rate than the BS modeled in Year 2012 (the numbers of buildings are identical in the two years). This results in lower energy losses from the buildings and, therefore, a greater potential for storing the thermal energy and, thereby, activation of DR. Therefore, it can be stated that the potential for space heating DR will be greater in a future with high-thermal-performance buildings. Although, it remains unclear as to what extent this potential will be needed/utilized in a possible future with significantly lower space heating demand from buildings.

The results from **Paper III** show that the DR achieved by allowing for upward temperature deviations of up to 3°C (*DR 3°C* scenario) affects the system heating load by smoothening the daily heat load variations to a greater degree than the DR achieved by allowing upward temperature deviations of up to 1°C (*DR 1°C* scenario). Figure 10 shows that the Relative Daily Load Variations (RDLVs) decrease in the *DR 3°C* and *DR 1°C* scenarios by 31% and 18%, respectively, as compared to the *Ref.* scenario. The modeling results indicate that the largest daily heat load variations mainly occur during the spring-autumn months of the year (area **a** of Figure 10), while during the winter months, the variations are less severe (area **b** of Figure 10). It is clear that the DRs obtained through overheating the buildings by 1°C or 3°C decrease the heat demand variations to similar extents during the spring-autumn period; this is true for area **a** of Figure 10. In area **b** of Figure 10, the DR of the buildings has a weaker effect on the heat demand variations. This is mainly due to the buildings having a greater DR potential during the spring/autumn period than during the winter period, i.e., the stored thermal energy during the spring/autumn period can be spread out over a longer time period due to lower energy losses from the buildings. Area **c** in Figure 10 indicates that the space heating DR in the *DR 3°C* scenario has a sufficiently high capacity to smoothen completely some of the intraday heat demand variations. This constant heating demand means that the generation of heat can be optimized more easily and scheduled to ensure the optimal economic and/or environmental performance (if other influential parameters, e.g., electricity price, vary insignificantly).

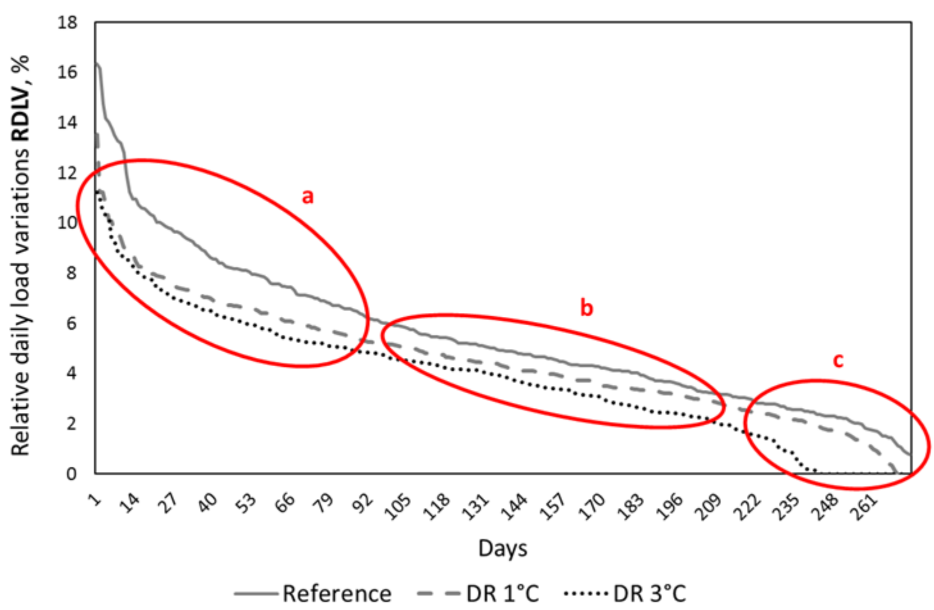

Fig. 10. The Relative Daily Load Variations (RDLVs), sorted in descending order, for the investigated DH system of Gothenburg, as obtained from the modeling for the *Ref., DR 3°C* and *DR 1°C* scenarios. Source: **Paper III**. Note that the modeled period is limited to 273 days, excluding the summer months.

The results from **Papers III** and **IV** indicate that the degrees to which some parts of the BS are activated for DR and some are not activated depend on the building type. The results show that the modeled MFDs and NRBs take part in DR more actively than do the SFDs. From **Paper IV**, the average yearly indoor air temperatures in the MFDs and NRBs in the *Tup* scenario are higher than in the *Ref.* scenario, by 0.3°C and 0.4°C, respectively. For the SFDs, this difference is 0.1°C. These results reflect the fact that the MFDs and NRBs have greater thermal capacities (time constants) than the SFDs and, therefore, greater potentials for storing energy. The SFDs, owing to their lighter structures and higher surface area-to-volume ratios, are less-suitable for DR[4].

5.2.2 The effects of space heating demand flexibility on the DH system

The smoothening of the total heating demand of the DH system provided by the flexible space heating demand in buildings has a significant impact on the level of heat generation in the DH

[4] The SFDs, in turn, are more suited to utilizing the potential for reducing the indoor air temperature with the purpose of reducing the total space heating demand. For more details, see **Paper IV**.

system. The main impacts of the DR on the operation of the DH system are increased heat supply from the base-load units and decreased heat generation from the peaking HOBs. Figure 11 shows the number of startups for the small-scale gas-fired CHP plant, the HPs, and the peaking HOBs (aggregated) available in the DH system of Gothenburg as of Year 2012 (**Paper III**), for the *Ref.*, *DR 1°C*, and *DR 3°C* scenarios. The results indicate that allowing for DR *via* +1 °C temperature deviations results in a significant drop in the number of startups required for the heat generation units. Peaking HOBs are affected the most, in that the number of startups for the wood-fired HOBs can be reduced by 80%, whereas the use of fossil fuel-fired HOBs can be avoided entirely. From Figure 11, it can be noted that increasing the allowed indoor-temperature deviations by up to 3°C (*DR 3°C* scenario) has little additional impact on the number of startups, as compared to the allowed 1°C deviations. The results also indicate that the utilization rate of the base-load waste-heat technologies increases in the scenarios with DR, as compared to the *Ref.* scenario. This results in a reduced number of operational hours and an increased utilization factor for the dispatchable units (CHP plants, HPs, and HOBs).

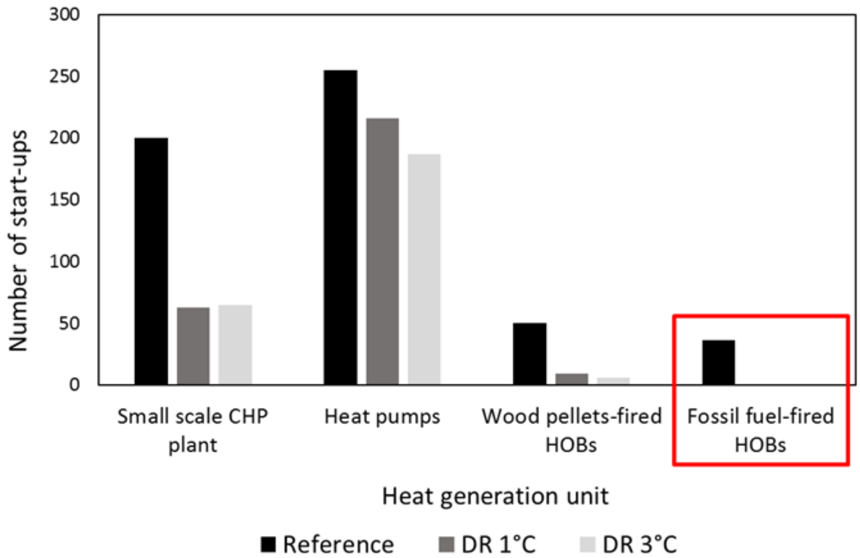

Fig. 11. Numbers of startups for the heat generation units in the DH system of Gothenburg, as obtained from the modeling for Year 2012 for the *Reference*, *DR 1°C*, and *DR 3°C* scenarios. Source: **Paper III**.

The modeling results from **Paper IV** show similar effects of the activated DR in buildings on the operation of the DH system as of Year 2050. The results show that the total number of startups of the dispatchable heat generation units (HPs and electric boilers) decreases by 52% in the scenario with DR *via* +3°C allowed temperature variations, as compared to the *Ref.* scenario with no DR. The total operational hours of the HPs and electric boilers are around 27% less in the scenario with DR than in the *Ref.* scenario. Considering that the compositions of the DH system in Years 2012 and 2050 are different even if the effects of DR on the operation of the heat generation units are similar, it seems likely that flexible demand from buildings will be beneficial for DH systems as long as there are heat load variations and an evident merit order of the heat generation units.

The operational changes that the investigated DH system undergoes due to the integration of flexible demand into the supply are associated with economic benefits. Figure 12 shows that the modeled total yearly running cost of the DH system in Year 2012 (**Paper III**) would have been up to 5.5% lower if the DR in buildings had been activated (*DR 3°C* scenario compared to the *Ref.* scenario). The modeling results from **Paper IV** show that the total yearly running cost of the DH system as of Year 2050 could be up to 8.5% lower in the *Tup* scenario (recall that the *Tup* scenario is identical to the *DR 3°C* scenario in **Paper III**, i.e., upward temperature deviations of up to 3°C are allowed), as compared to the *Ref.* scenario. In addition to the explicitly modeled economic benefits of DR, the more-stable operation in combination with fewer startups of the heat generation units would likely decrease the wear on the equipment, thereby reducing the need for maintenance and repairs. This would extend the lifespans of the units and lead to even greater savings.

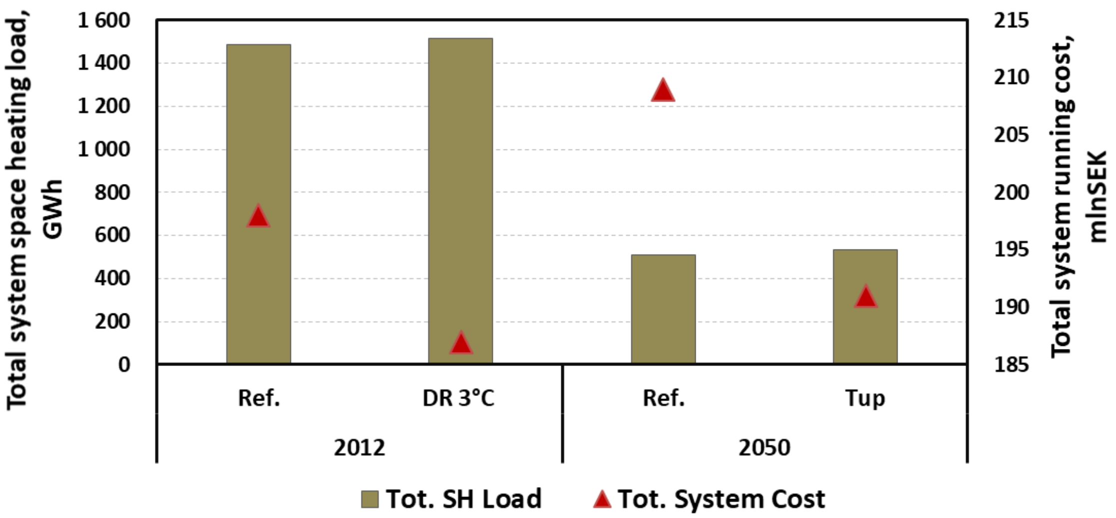

Fig. 12. The total space heating load and total system running cost of the investigated DH system of Gothenburg, as obtained from the modeling of the *Ref.* and *DR 3°C* for Year 2012 (**Paper III**) and the *Ref.* and *Tup* scenarios for Year 2050 (**Paper IV**). Both *Ref.* scenarios do not allow for DR, while *DR 3°C* and *Tup* scenarios allow for DR *via* +3°C temperature variations in buildings.

From Figure 12, it is clear that the total system space heating load in both scenarios is significantly lower in Year 2050, as compared to Year 2012. This is mainly due to the improved energy performance of the investigated BS, which results from the implementation of the ECMs modeled in **Paper V**. It is also noteworthy that the total running cost of the DH system is higher in Year 2050, as compared to Year 2012 (when scenarios with and without DR are respectively compared), even though the space heating load is much lower. While this obviously depends on various factors, it mainly reflects the differences between the assumed current and future fuel and electricity prices. With that said, it should be stressed once again that the presented results should not be taken as descriptive (for Year 2012) or prescriptive (for Year 2050), but rather as an indication that the space heating load from the investigated BS can be expected to decrease in the future and that the DR from buildings has the potential to benefit the operation of the DH system.

It is evident from Figure 12 that the total yearly space heating load is slightly higher in the scenarios with activated DR in buildings than in the respective reference scenarios. This is because the use of DR *via* only upward temperature deviations from the set-point value results in higher average indoor temperatures in the buildings and, therefore, higher energy losses and a higher space heating load. This, however, can be counteracted if downward temperature deviations are also allowed.

5.3 Space heating demand flexibility vs. centralized TES in DH systems

5.3.1 Demand response in buildings vs. use of a hot-water tank

The results from the modeling in **Paper II** confirm the findings described earlier in **Papers III–IV**, i.e., flexible space heating demand that is achieved through controlled indoor temperature deviations in buildings influences the total system heating load by effectively smoothening its variations. Figure 13 shows the relative daily load variations (RDLVs, Figure 13 a) and the relative weekly load variations (RWLVs, Figure 13 b), in both cases organized in descending order, as obtained from the modeling for the *Ref.*, *HWT*, and *BITES* scenarios in **Paper II**. In the *Ref.* scenario, no TES is applied, while in the *HWT* and *BITES* scenarios, the centralized HWT and thermal storage in buildings – BITES, are applied respectively. The results for the *BITES* and *HWT* scenarios show that the RDLVs decrease in total by 19% and 20%, respectively, as compared to the *Ref.* scenario, whereas the RWLVs decrease by 10% and 17%, respectively. This indicates that both TES types confer benefits upon the DH system investigated, by smoothening the short-term (i.e., daily) heat load variations with equal efficiencies. However, the performance of the HWT is superior in that it can smoothen the load variations on longer time-scales, i.e., up to weekly load variations. The greater ability of HWT to smoothen weekly net load variations is attributed to its lower energy losses to the outdoor air, as compared to the losses from BITES, and, consequently, longer periods of time when HWT can remain charged with heating energy.

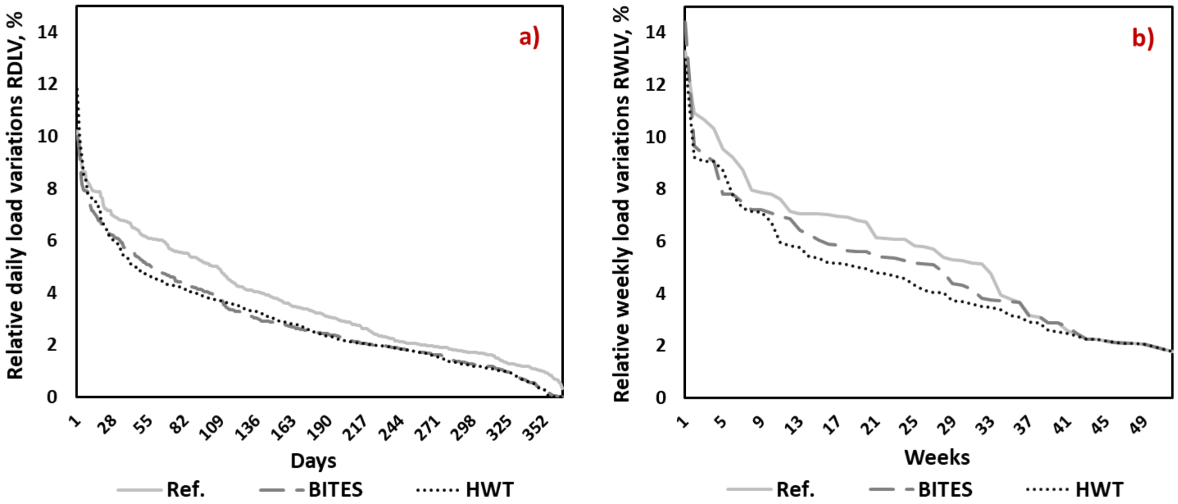

Fig. 13. The **a)** relative daily load variations and **b)** relative weekly load variations of the investigated DH system in the *Ref., BITES,* and *HWT* scenarios, as obtained from the UCS modeling (shown in descending order). Source: **Paper II**.

It is also noteworthy from Figure 13 that in both the *BITES* and *HWT* scenarios, the RWLV values never drop below 2%. This indicates that the capacity of BITES or HWT is not sufficient to flatten the heating load of the investigated city of Gothenburg for 1 week or longer. If it becomes necessary to eliminate completely the weekly heat-load variations, one should consider the option of installing a larger TES unit, e.g., a seasonal pit-based TES.

The modeling results from **Paper II** indicate that the availability of a TES in DH systems leads to economic benefits, i.e., a decreased total system running cost, as also observed in **Papers III** and **IV**. The results indicate that the utilization of BITES and HWT can lead to reductions of 1% and 2%, respectively, in the total system running cost of the DH system of Gothenburg, as compared to the case in which no TES is available. It is evident that the savings observed in **Paper II** are lower than the savings reported in **Papers III** and **IV**. While there are several reasons for such differences in savings, the main ones are that different types of modeling were applied in **Paper II** as opposed to **Papers III** and **IV,** and that only a fraction (40%) of the BS of Gothenburg was represented in **Paper II** as BITES (the capacity of HWT matched the capacity of BITES), while in **Papers III** and **IV** the whole BS was considered.

In light of the presented findings on the smoothening effects of BITES and HWT, it is of importance to understand those aspects for which the respective utilization strategies of these two TES types differ. The results show that the charging patterns for both TES types are very similar in terms of both magnitude and frequency of occurrences (*cf.* Figure 14), while the storage level and the discharging patterns differ noticeably. The results indicate that HWT is, on average, kept charged (stores heat) at a level that is more than double the level for BITES, i.e., the average energy levels of BITES and HWT over the modeled year are

270 MWh and 590 MWh, respectively. Both HWT and BITES are being charged for around 2,000 h over the year (out of a total of 8,760 h), with average charging rates of 43 MW/h and 49 MW/h, respectively. The discharging of BITES occurs for 4,400 h, with an average discharge rate of 18 MW/h, while HWT is discharged for only 2,000 h, with an average discharge rate of 46 MW/h. The discharging of BITES is limited by the rate of heat exchange between its components, i.e., the shallow storage (the indoor air and building internals) and deep storage (the building envelope and the core) components. When BITES is almost depleted the situation arises that the shallow storage is completely discharged, i.e., the indoor air and other components of the shallow storage have reached the set-point temperature, even though the deep storage is still charged, i.e., the temperature of the structural elements is still higher than the set-point temperature. Thus, discharge of BITES occurs at the rate of heat exchange between the building core and the indoor environment. These results indicate that HWT can be considered as a more flexible form of TES, as compared to BITES, since the capacity of the former is available in full for charging/discharging at any time-step, which should prove beneficial for the DH system operator.

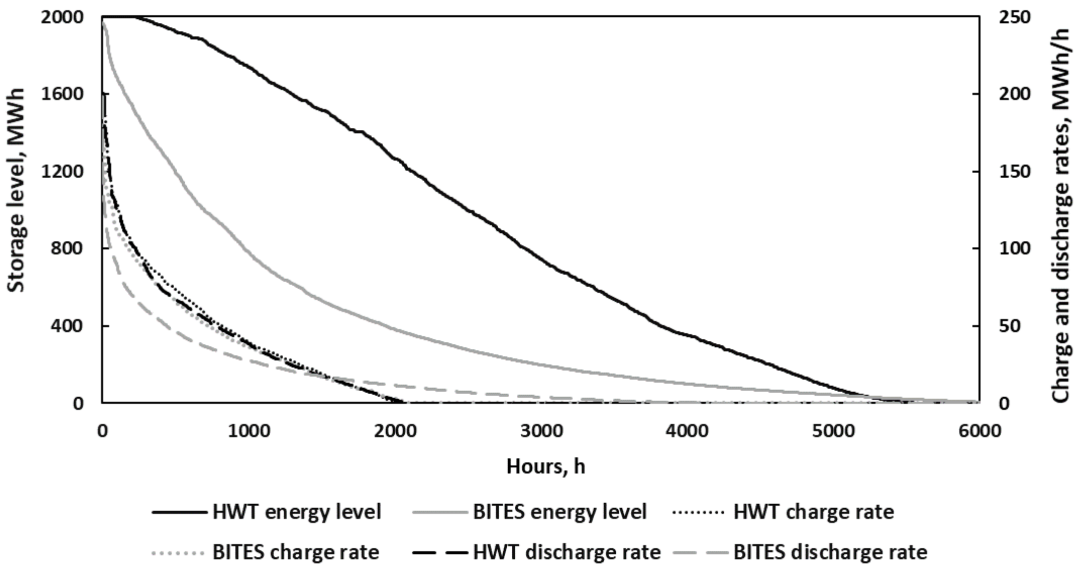

Fig. 14. Hourly charge and discharge rates and hourly storage levels of HWT and BITES, as obtained from the UCS modeling, given in descending order. Note that the *x*-axis only extends to 6000 hours (during the remaining hours, the values of the charge/discharge rates and the storage level are all zero). Source: **Paper II**.

5.3.2 Demand response in buildings vs. seasonal pit-based TES

The modeling results from **Paper V** indicate that an investment in a seasonal pit-based TES in the DH of Gothenburg is cost-effective from the long-term (until Year 2050) system development perspective. Figure 15 shows the duration of the total system heat generation, sorted in descending order, for the investigated DH system, as obtained from the EBUC model for the *Ref.* (no DR, no TES), *Tup* (with DR, no TES), *TES* (no DR, with TES), and *TES_Tup* (with DR, with TES) scenarios in **Paper IV**. It is clear that the availability of flexibility measures, both TES and DR from the buildings, results in more-stepwise duration curves, although the effect of TES is more pronounced. The plateaus of constant heat generation are noticeably longer in the scenarios with TES, which is attributed to the ability of TES to store heat between seasons, e.g., accumulate excess heat during the summer-time and discharge it during the colder months of the year. The modeling results show that the total numbers of operational hours of the dispatchable heat generation units (HPs and electric boilers) decrease by 39% and 41% in the *TES* and *TES_Tup* scenarios, respectively, as compared to the *Ref.* scenario (by 27% in the *Tup* scenario). The reductions in the total number of startups of the dispatchable units are also the largest in the scenarios with TES available in the DH system: the numbers of startups are reduced by 70% and 78% in the *TES* and *TES_Tup* scenarios, respectively, as compared to the *Ref.* scenario.

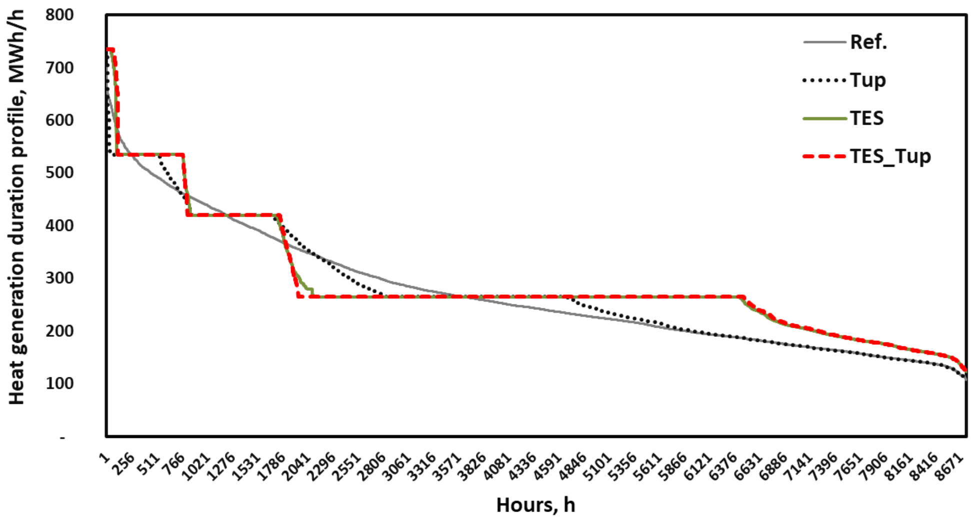

Fig. 15. The heat generation profiles, sorted in descending order, for the investigated DH system of Gothenburg, as obtained through the EBUC modeling for the *Ref., Tup, TES,* and *TES_Tup* scenarios. Modified from **Paper IV**.

As indicated in Section 5.2.2, the total yearly running cost of the DH system is decreased by 8.5% in the *Tup* scenario, as compared to the *Ref.* scenario, due to the activation of DR from the buildings. In the *TES* scenario, the total yearly running cost of the DH system decreases to a greater extent, i.e., by around 40%, as compared to the *Ref.* scenario. These results clearly indicate that the studied seasonal TES confers greater economic benefits on the DH system, in terms of reduced running costs, than does allowing for energy flexibility in the buildings, if comparing their individual effects.

The results for the *TES_Tup* scenario – the scenario with both DR from the buildings and seasonal TES being applied at once – indicate that the availability of a centralized TES in the

DH system alleviates the need for active DR (upregulation in temperature) from the buildings. This means that the economic gains from smoothening the dispatch in the DH system can be achieved using the seasonal TES alone. Thus, in the *TES_Tup* scenario, the total yearly running cost of the DH system decreases to the same extent as it does in the *TES* scenario, i.e., by around 40%, as compared to the *Ref.* scenario. However, the results from **Paper IV** show that if both upward and downward indoor temperature deviations in the buildings are allowed (as opposed to only upward deviations in the *Tup* and *TES_Tup* scenarios), the presence of the seasonal TES will make it possible to use the downregulation of the indoor temperature to achieve energy savings in all the building types[5]. Therefore, reductions in the energy use for space heating in future buildings can be expected from both the implementation of ECMs and operational energy savings that are achieved through indoor temperature deviations.

5.4 Interplay between DH systems and the power sector

Despite the benefits that DR in buildings and TES can provide to energy systems, their integration into heating systems is not yet common practice. Meanwhile, the interlinkage between DH systems and the power sector is already strong, especially in Scandinavia, where CHP plants and HPs are widely used for heat generation. In **Paper I**, the effects of present and future electricity prices, resulting from development of the power sector, on the operation of the DH system of Gothenburg (as of Year 2012) are investigated. Six scenarios are investigated that are defined by different electricity price profiles, which are influenced by an increase in the wind power penetration level (from the current 5% to a future 50% penetration level) and the potential phasing out of nuclear power (the last scenario) from the Swedish power system.

The results of the modeling indicate that the dispatch of the investigated DH system and the individual operational strategies of CHP plants and HPs are affected by both the average electricity price and price fluctuations. For a future with a higher average electricity price and increased frequency of periods with high prices for electricity, as compared to current prices, the modeling results indicate that there will be up to 25% higher total yearly heat generation from CHP plants and up to 20% lower generation from HPs. The main reason for this is the change in the merit order of these two technologies during periods with high electricity prices. CHP plants generate higher profits from sales of electricity at higher electricity prices, while HPs become more expensive to run. In contrast, during periods with low prices for electricity, HPs are already used as base-load units, so an additional drop in the price will only reinforce their position. These results indicate that having both CHP plants and HPs in DH systems will be economically beneficial in a future with volatile electricity

[5] More details can be found in **Paper IV**.

prices, since they will allow benefits to be accrued from both low and high electricity price periods.

The findings from **Paper I** indicate that there are additional benefits associated with having CHP plants in DH systems that have the possibility to vary their power-to-heat ratio. CHP plants with variable power-to-heat ratios can benefit from operating in an ‘‘electricity price-following” mode, in which electricity generation is prioritized over the generation of heat, during high-electricity-price periods. Figure 16 a shows the total yearly heat and electricity generation levels and the total numbers of operational hours for a gas-fired CHP plant with variable power-to-heat ratio available in the DH system of Gothenburg (RYA CHP plant), for all the investigated scenarios. In addition, Figure 16 b shows the operational modes of this unit in terms of the heat and electricity outputs for the scenario representing the reference Year 2012. In the scenario with the most variations in electricity prices and the highest average electricity price (“50% wind no NUC” scenario), the number of hours during which that CHP plant prioritizes electricity generation over heat generation and operates with the maximum possible electricity output (with electricity generation following the horizontal line in Figure 16 b) is double the number of hours during which the heat output is maximized. Furthermore, the heat output from that CHP plant increases by approximately 25%, whereas the electricity output is doubled compared to the other scenarios investigated.

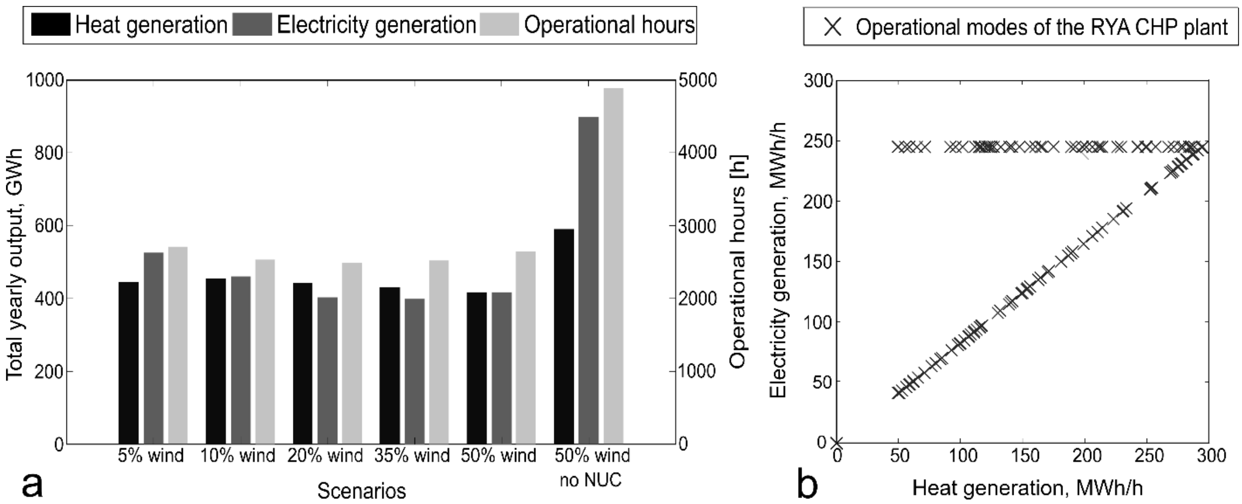

Fig. 16. The relationship between heat and electricity generation in a gas-fired CHP plant with a variable power-to-heat ratio. a) Total yearly heat and electricity generation, together with the total number of operational hours, as obtained from the modeling of six investigated scenarios. b) The operational modes, representing the heat generation and respective electricity generation levels, as obtained from the modeling of the scenario for Year 2012. Source: **Paper I**.

To summarize, the modeling results from **Paper I** indicate that the operation of DH systems will most likely be significantly affected by variations in the electricity price profiles. However, the outcomes from these changes could be beneficial, both to the DH system owners and to the power system operators. On the one hand, the DH owners can make extra profit by providing flexibility services to the power sector *via* the smart dispatch and operation of their CHP and HP capacities, i.e., generating electricity when the price is high and running HPs when the price is low. The power sector, on the other hand, can benefit from having an additional, rather reliable provider of flexibility services.

6. Conclusions

At the beginning of this thesis, the hypothesis was put forward that considering the demand and supply sides at the same time when investigating the development of urban heating systems has the potential to increase resource efficiency and reduce the cost of heat supply. Based on the results of this work, the main conclusion is that this hypothesis is valid. Another tested premise was whether the flexibility within DH systems and sectoral coupling between DH systems and the electric power system could provide techno-economic benefits to the energy system. It can be concluded that this premise is also valid.

The results of this work indicate that the least costly development of the urban heating system, i.e., BS and DH system of Gothenburg considered together, up to Year 2050 is achieved if only fuel and electricity price developments drive demand reductions, in other words that no targets are set for space heating demand reductions. However, this would obviously compromise the possibilities for Society to achieve general sustainability goals. Thus, even though the results of this work indicate that demand reductions of around 25% already by Year 2030, as compared to Year 2020, can be expected even without the demand reduction targets, it seems likely that further ECMs will be implemented due to policy. The results show that meeting the Swedish or European energy demand reduction targets in the investigated buildings will result in more investments in ECMs, leading to a significantly lower total SH demand, i.e., reductions of around 60% by Year 2050, as compared to Year 2020, and fewer investments in heat generation capacities.

The modeling results also show that irrespective of the space heating demand target levels, the least costly development of the DH system and BS will be achieved through a combination of investments in ECMs for the buildings, new heat generation units, and energy storage capacities in the local DH system. It is shown that the most economically attractive ECMs for the BS are the installation of ventilation heat recovery systems in MFDs and NRBs and the insulation of roofs in all the building types. For the supply side, the results demonstrate that the cost-optimal heating technologies to be invested in for the local DH system are heat pumps, electric boilers, and a seasonal pit-based TES. However, depending on the relationships between future electricity and fuel prices, investments in CHP plants may be prioritized at the expense of heat pumps and electric boilers.

From the modeling results presented here, it is clear that if the DR in buildings is realized, by allowing indoor temperature deviations from the set-point temperature, it could have a significant impact on the total system heating load of the city. The two methodologic approaches used in this work, i.e., heat supply optimization modeling with integrated DR via explicit calculation of the space heating demand *vs.* representation of the BS as a TES, indicate that the main outcome of having flexible heating demand in buildings is effective smoothening of the total system heating load. Smoothening, which is defined here as decreases in the number and amplitude of the heat-load variations, is achieved via "peak shaving" and "valley filling". The results indicate that the possibility to control the indoor temperature deviations by as little as +1°C from the set-point value can confer a significant, i.e., up to 20%, decrease in the daily load variations. Further increasing the DR potential *via* upward temperature deviations of up to 3°C can provide even greater smoothening effects, albeit with diminishing returns. Furthermore, we show that the impact from DR in buildings is strongest during the period when daily heat-load variations are greatest, i.e., during the spring and autumn months, and depends on the type of building. The results indicate that the MFDs and NRBs manifest greater DR potentials *via* upward temperature deviations than do SFDs. This is due to their higher thermal capacities and, therefore, greater potentials for storing the energy.

The results of this work reveal that the short-term (i.e., daily) heat load smoothening effects of utilizing the investigated BS for DR are comparable to the effects of a centralized HWT. However, if the goal is to moderate the heat-load variations on a longer time-scale, e.g., weekly variations, storage in HWT is superior (due to the lower energy losses). Moreover, HWT is considered to be the more-flexible heat storage option because it is not limited by having an additional heat exchange stage, as is the case for buildings, i.e., heat exchange between the building envelope and the internals. The results further reveal that a seasonal TES can provide even greater benefits to the investigated DH system by not only moderating short- to mid-term heat load variations but also by storing heat between seasons, accumulating excess heat during the summer-time and discharging it during the colder months of the year. This can be of particular importance in systems that have access to potential waste heat, which otherwise would be lost during warm periods of the year. We also show that if a seasonal TES and DR from buildings were applied at the same time, these TES options could become complementary from a systems perspective, i.e., upward indoor temperature variations in buildings would be alleviated due to the presence of the TES, while downward temperature deviations leading to operational energy savings would be activated. However, these benefits of a seasonal TES should be considered in the light of the significant investment cost before an investment decision is made.

The modeling results obtained in this work show that flattening the total system heating load, as achieved by using both flexible space heating demand from buildings and a centralized TES, results in more-efficient heat generation. We show that the heat supply from base-load units increases, while the output from peaking units decreases in all the investigated scenarios with activated DR and/or a TES available in the system. Following these changes in the heat generation strategies, there is a decrease in the total running cost of the investigated DH system. Depending on the DH system composition and the share of the BS activated for DR, a decrease of 1%–8% in the total yearly cost of heat generation can be expected. We also show that applying a centralized TES can result in even greater economic benefits. For example, utilization of a seasonal TES in the modeled DH system of Gothenburg as of Year 2050 has the potential to decrease the running cost of the system by up to 40%, as compared to the setup without the TES.

Finally, the synergy between DH systems and the power sector is shown to be mutually beneficial. Smarter, flexible utilization of CHP plants and HPs could bring additional economic benefits to DH systems operators by increasing the electricity generation from CHP plants during periods of high electricity prices (usually corresponding to periods with low generation from variable renewable energy resources) and by increasing heat generation in HPs when the price is low (periods with excess generation from variable renewables). Simultaneously, the flexibility services provided by DH systems could help to accommodate more variable renewable energy resources within the power system.

7. Reflections on further research

In this thesis, the cost-optimal development of a local BS and DH system is investigated based on optimization modeling that is subject to a number of constraints and assumptions, which obviously influence the results and conclusions drawn in this work. In this work, the outdoor air temperature and solar irradiation profiles applied to all the modeled years (up to Year 2050) are based on measurements made in the past and, therefore, do not account for any climate change impacts. Given that the global temperature is expected to increase in the future, the energy demand for space heating in buildings will obviously be reduced, while the demand for cooling will increase. This will have an impact on the rate of implementation of ECMs and, consequently, on the investments in and operation of DH systems. Therefore, further research on the impact of climate change on the energy demand/generation balance in urban heating systems is of interest (can be inspired by previous works [93, 94]).

The ambition to transform the current so-called '3rd generation' DH systems to '4th generation' DH systems has been discussed for a while [13, 14]. One of the characteristics of a 4th generation DH system is a low temperature level, i.e., supply and return water temperatures as low as 50°C and 20°C, respectively. Reducing the temperature raises a number of challenges, for example, delivering the same amounts of heat at lower temperature requires higher water flow rates and thus larger pipes. At the same time, a lower water temperature results in lower thermal losses to the ground. These and other advantages and disadvantages of reducing the temperature will influence the compositions and operational strategies of DH systems and warrant further investigation. Moreover, elucidating the linkages between low-temperature heat deliveries and low-energy buildings is likely to provide new insights into the synergy between demand and supply.

Another issue that would be interesting to address is the representation of hot-water demand in the investigated buildings. It is common practice to treat the demand for hot water as a single demand profile, as is the case in this thesis, given that space heating still represents the main energy demand in buildings. However, with more low-energy buildings being constructed and connected to DH systems, the share of the hot-water demand increases in the total energy consumption profiles of buildings. Therefore, characterization and explicit modeling of the various end-uses of hot water in buildings would likely reveal new facets of energy consumption in buildings and potential DR strategies derived from the hot-water demand.

When studying the potential of space heating DR that is achieved through allowing indoor temperature deviations, the assumption is made that the thermal comfort of the occupants is not jeopardized. The allowed indoor temperature deviations applied in this work could precipitate a situation in which the indoor temperature in a building can change by up to a few degrees in just one hour. Obviously, people perceive changes in the surrounding temperature differently, and the few hours of temperature increase or decrease could be unacceptable to some individuals while being tolerable to others. However, the acceptance rate could change if some sort of motivation, e.g., financial incentives, was offered to the people exposed to the temperature variations. With this said, some interdisciplinary research projects investigating the willingness of people to accept temperature variations (can be inspired by previous works [95, 96]) and the impact of this acceptance on the cost of DR activation (if financial incentives for occupants are introduced) could provide new direction for decision-makers as to how to ease and accelerate the energy system transition.

Finally, the presented results are based on the BS and DH systems of Gothenburg, which obviously makes them case-specific (although some general conclusions are drawn). Application of the developed modeling methodology to other local heating systems and building stocks, as well as the scaling up of the research to the national level and to other countries could provide new perspectives and reveal new dependencies.

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